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Naval Aviation is in the midst of a major transformation as it attempts to come to terms with the demands of maintaining operational readiness in the face of diminishing budgets and reduced manning. Diminishing operating and procurement budgets mean that Naval Aviation is for the most part "making do" with existing aircraft. Over the past decade, one in four Naval Aviation mishaps were partially attributable to maintenance error. The present operating environment underscores the need to address maintenance error and its causes. The current study accomplishes three things. First, it evaluates 470 Naval Aviation mishaps with distinct maintenance error correlates. Second, it categorizes those errors using a taxonomy based upon current organizational and psychological theories of human error. Third, it mathematically models the consequences of these errors and uses the models to (a) predict the frequency with which maintenance-based mishaps will occur in the future and (b) approximate the potential cost savings from the reduction of each error type.

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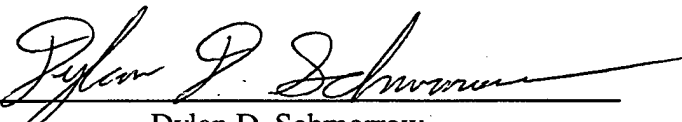B.S., Western Michigan University, 1989

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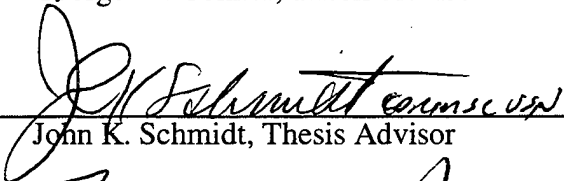
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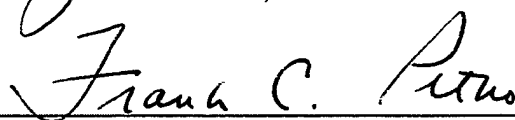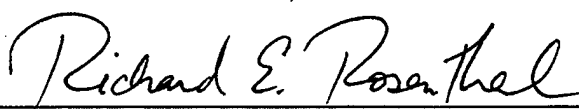
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ABSTRACT

Naval Aviation is in the midst of a major transformation as it attempts to come to terms with the demands of maintaining operational readiness in the face of diminishing budgets and reduced manning. Diminishing operating and procurement budgets mean that Naval Aviation is for the most part "making do" with existing aircraft. Over the past decade, one in four Naval Aviation mishaps were partially attributable to maintenance error. The present operating environment underscores the need to address maintenance error and its causes.

The current study accomplishes three things. First, it evaluates 470 Naval Aviation mishaps with distinct maintenance error correlates. Second, it categorizes those errors using a taxonomy based upon current organizational and psychological theories of human error. Third, it mathematically models the consequences of these errors and uses the models to (a) predict the frequency with which maintenance-based mishaps will occur in the future and (b) approximate the potential cost savings from the reduction of each error type.

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LIST OF ACRONYMS

AGM   Aircraft-Ground Mishap

AMB   Aircraft Mishap Board

DOD   Department of Defense

FM   Flight Mishap

FRM   Flight-Related Mishap

FY   Fiscal Year

MIR   Mishap Investigation Report

MRM   Maintenance-Related Mishap

NAVAIR   Naval Air Systems Command

EXECUTIVE SUMMARY

Naval Aviation is in the midst of a major transformation as it attempts to accommodate the demands of maintaining operational readiness in the face of diminishing budgets and reduced manning. The effects of Naval Aviation mishaps are significant in terms of loss of life, money, mission readiness, and mission capability. Over the past decade, one in four Naval Aviation mishaps were partially attributable to maintenance error. Throughout the past decade, Naval Aviation leadership has focused attention on the role of aircrew error and has seen a concomitant decrease in mishaps. However, leadership has not focussed on maintenance-related mishaps (MRMs) when, in point of fact, the maintenance of existing platforms will become increasingly important. Unless dramatic changes occur in the current operational environment, Naval Aviation will be confronted with a diminishing number of fleet aircraft that are rapidly aging.

The baseline methodological tool of this thesis is the Human Factors Accident Classification System (HFACS). The HFACS is a contemporary data collection and organizational instrument designed to aid in the

analysis of Naval Aviation mishaps. It integrates theories and models derived from the psychological and organizational literature to produce a taxonomic tool with which an accident investigator can categorize the various forms of human error that may have been related to the mishap. The Maintenance Extension used in the present study is simply a variant of the HFACS. It is designed to focus the classification system on human error forms associated with maintenance.

The Maintenance Extension of the HFACS was used to evaluate human error directly associated with maintenance actions in 470 Naval Aviation MRMs. The analysis identified five human error categories out of ten that were most frequently associated with MRMs. These categories were *error*, *squadron*, *violation*, *unforeseen*, and *crew-resource management*. At least one of these five error types was present in over 95 percent of the 470 mishaps studied.

Information generated from the classification of human error was used to develop mathematical models which were then employed to develop a notional cost estimate associated with human errors in maintenance-related Naval Aviation mishaps. These models were, in turn, used with archival maintenance error data to gauge

the potential impact of maintenance error reduction programs. Taken together, the taxonomic analysis and the model development accomplished two things. First, they identified the forms that maintenance error takes and the conditions under which they occur. Second, they identified the optimal point to employ intervention strategies to generate the most cost savings.

A variable Poisson process model was chosen as the simplest model that was suitable for predicting future mishaps. Probability tables for the number of future mishaps were derived from the density function associated with the means of the hypothetical Poisson process model. The average number of mishaps per year predicted by this model over the next five years ranged from 22 to 33 per year. Based on these values, the expected cost of MRMs for fiscal year 1998 was nearly 60 million dollars and well over 200 million for FY98 through FY02. An analysis of potential reductions associated with these error types revealed that cutting their occurrence by as low as 10 percent can save millions of dollars a year.

ACKNOWLEDGEMENTS

I. INTRODUCTION

A. OVERVIEW

Naval Aviation is in the midst of a major transformation as it attempts to come to terms with the demands of maintaining operational readiness in the face of diminished budgets and reduced manning. Losing human or material assets because of an accident or mishap is amplified in today's operating environment. This is especially true for the U.S. Navy and Marine Corps whose strategy of "Forward Presence" require that they will be first on the scene in times of crisis. In particular, the record will show that Naval Aviation is most likely to be called upon to project force during crises. These operational requirements and Naval Aviation's response to them impact the aircraft, the aircrews, the maintainers who prepare the aircraft for flight, and the equipment those technicians use to maintain it (Nutwell and Sherman, 1997).

Naval Aviation's leadership has focused much attention on the role of aircrew error in mishaps over the past several years, and this has led to a dramatic

reduction in the overall Class A Flight mishap rate[1] (Department of the Navy, 1997a). These reductions are attributable to several focused intervention programs and strategies aimed at reducing the causes of aircrew error; for example, the establishment of aircrew coordination training events and human factors councils. Unfortunately, such efforts do not address maintenance error and the conditions that cause it. Yet, during the past decade, maintenance error contributed to one in every four Naval Aviation mishaps.

Diminishing operating and procurement budgets mean that Naval Aviation must "make do" with existing aircraft. And, as operational requirements increase, these aircraft tend to be flown less to extend their life and reduce operating costs (Lockhardt, 1997). Additionally, older aircraft generally require more maintenance, more inspections, more major overhauls, and more operating limitations. This increased maintenance support is required to offset an aging fleet, which in turn underscores the need to address maintenance error and its causes. The need to preserve aviation assets and to address the problems associated with the aging aircraft fleet prompted Naval Aviation leadership to

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[1] Definitions can be found on page 6.

thoroughly examine aviation maintenance plans, policies, procedures, and practices.

Today's operational and budgetary climate demands management attention be focused on maintenance-related mishaps (MRMs). Naval Aviation must identify the types of maintenance errors associated with mishaps, and then implement intervention programs and strategies aimed at reducing the causes of these errors. The present study will take a step toward that goal. It will identify human error forms associated with past MRMs and then develop mathematical models to evaluate the most likely impact a program of focused maintenance error reduction might have.

When evaluating the general impact of human error on any given outcome variable, it is methodologically necessary to first differentiate between classes of error forms and then specify those forms associated with any particular mishap. Based upon that taxonomy, mathematical models can then be developed to predict the frequency of MRMs, project the magnitude of their associated costs, and forecast the impact various intervention strategies may have upon Naval Aviation assets. This thesis did the aforementioned and showed that reductions in certain maintenance errors by as

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little as 10 percent may save Naval Aviation millions of dollars annually.

B.   BACKGROUND

The current Commander of the Naval Air Systems Command (NAVAIR), Vice Admiral Lockhardt, stated that the average age of naval aircraft will continue to increase into the 21st century. He predicts that mission capability and readiness is directly coupled to this clear negative trend if left unchecked. To counter this negative trend, NAVAIR is investigating the potential impact of implementing new maintenance concepts including phased depot maintenance, the acceleration of depot work and inspection, and depot maintenance efficiencies from reliability centered maintenance actions. NAVAIR has also solicited the fleet for new ideas and has directed greater command focus on aviation maintenance issues. These efforts underscore the fact that NAVAIR must, and is, identifying and directing interventions to accommodate maintenance-related hazards and risks.

C.   PROBLEM STATEMENT

The present thesis will address Naval Aviation MRMs in a systematic fashion. Accordingly, it identifies the

human-error types that contribute to MRMs and investigates the following areas:

1. The form of human errors, both direct and indirect, that lead to maintenance-related aviation mishaps;

2. The ability of stochastic models to predict future MRMs and mishap costs;

3. The type of intervention strategy or strategies — personnel training, improved policies and procedures, and command climate — that would "best" reduce MRMs; and

4. The impact reducing prevalent forms of maintenance errors by 10, 20, and 30 percent would have on future mishaps and overall costs to Naval Aviation.

D.   OBJECTIVE

The present study examines Naval Aviation MRMs to assess the nature of human error involvement and to determine potential cost savings of intervention strategies designed to reduce these errors. The primary objective is to determine which forms of human error are most prevalent, most costly in terms of loss of life, and most expensive in overall cost. A secondary objective is to present a methodology for modeling and assessing the potential benefits of proposed intervention strategies.

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E. DEFINITIONS

This study used the following definitions (Department of the Navy, 1997b):

Naval Aircraft. Refers U.S. Navy, U.S. Naval Reserve, U.S. Marine Corps, and U.S. Marine Corps aircraft.

Mishap. A naval mishap is an unplanned event or series of events directly involving naval aircraft, which result in 10 thousand dollars of greater cumulative damage to naval aircraft or personnel injury.

Mishap Class. Mishap severity classes are based on personnel injury and property damage.

   a. Class A Severity. A mishap in which the total cost of property damage (including all aircraft damage) is $1,000,000 or greater; or a naval aircraft is destroyed or missing; or any fatality or permanent total disability occurs with direct involvement of naval aircraft.

   b. Class B Severity. A mishap in which the total cost of property damage (including all aircraft damage) is $200,000 or more, but less than $1,000,000 and/or a permanent partial disability, and/or the hospitalization of five or more personnel.

   c. Class C Severity. A mishap in which the total cost of property damage (including all aircraft damage) is $10,000 or more but less then $200,000 and/or injury results in one or more lost workdays.

Mishap Categories (Types). Naval aircraft mishap categories are defined below:

   a. Flight Mishap (FM). Those mishaps in which there was $10,000 or greater DOD aircraft damage or loss of a DOD aircraft, and intent for flight for DOD aircraft existed at the time of the mishap. Other property

damage, injury, or death may or may not
have occurred.

b. <u>Flight Related Mishap (FRM)</u>. Those mishaps
in which there was less than $10,000 DOD
aircraft damage, and intent for flight
(for DOD aircraft) existed at the time of
the mishap, and $10,000 or more total
damage or a defined injury or death
occurred.

c. <u>Aircraft Ground Mishap (AGM)</u>. Those
mishaps in which no intent for flight
existed at the time of the mishap and DOD
aircraft loss, or $10,000 or more aircraft
damage, and/or property damage, or a
defined injury occurred.

F. SCOPE AND LIMITATIONS

This study examines Flight Mishaps (FM), Flight-
Related Mishaps (FRM), and Aircraft-Ground Mishaps (AGM)
which occurred from FY90 to FY97 and were caused, in
part or wholly, by maintenance errors. The focus of the
work is on maintenance operators. Personal injury
accidents are not considered.

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II. LITERATURE REVIEW

A. OVERVIEW

The literature review for this research included journals and textbooks covering the subjects of accident prevention, reporting, investigation, and causation. The purpose of this literature review is to provide an overview of the historic and current theories and practices concerning mishaps and to provide a rational basis to classify maintenance error.

B. ACCIDENT PREVENTION

1. Origins and Practice

Interest in accident prevention did not begin until the beginning of the 20th century when employers realized that it was less expensive to prevent accidents than to pay for their consequences (Petersen, 1978). Organizations confronted with the challenge of how best to protect themselves and their employees from accidents have two options, namely, insurance and accident prevention programs (Pate-Cornell, 1996). Organizations typically employ both options (Kanis and Weegels, 1990), but the U.S. Navy does not purchase insurance and accordingly, must absorb the costs of any losses.

Accident prevention initiatives therefore, are the primary means Naval Aviation has to reduce costs associated with mishaps.

Accident prevention was initially based on the widely held notion that people committing unsafe acts, not their working conditions, were to blame for most accidents (Heinrich, 1941). This thinking fostered a preoccupation with assigning blame to people; a practice which hindered the development of systematic accident prevention well into the later half of this century (Manuele, 1981). Narrowly focusing on people and not on the environment in which they operate, tended to obscure a subset of associated causal factors. This is particularly true with systems that chronically expose individuals to hazards (Schmidt, 1987). Although there have been substantial advances in accident prevention in recent decades, the practice of blaming individuals for the accident, rather than the conditions associated with it, persists. This practice must be overcome and accidents must be analyzed in terms of the systems in which they occur.

2. Systems Engineering

The most effective accident prevention strategies employ systems engineering (Hawkins, 1987). The systems engineering approach was developed in the 1950's as part of the United States military's large-scale weapons programs. Systems engineering transforms operational needs into a description of system parameters and integrates them to optimize overall system effectiveness (Edwards, 1988). In addition, it focuses the level of analysis on the smallest identifiable system components and how these components interact (Bird, 1974). The strategy of focusing on the system through the development of well-defined system components exposes information that would have remained unknown without a system-level evaluation (Miller, 1988).

Systems engineering pays attention to the strengths and limitations of the human operator as an integral part of the system. The literature suggests that nearly 90 percent of accidents are attributable to human error (Heinrich, Petersen, and Roos, 1980; Hale and Glendon, 1987). Therefore, evaluating human factors associated with accidents can contribute to the understanding of systems and how they fail.

3.   The SHEL Model

In the early 1970's the "SHEL Model" of system design was developed to provide a better way to evaluate failures in human-machine systems (Edwards, 1988). The "SHEL Model" identifies and defines four system dimensions: Software, Hardware, Environment, and Liveware. Edwards (1988) defines SHEL concepts as follows:

1. Software: the rules, regulations, laws, orders, standard operating procedures, customs, practices, and habits that govern the manner in which the system operates and in which the information within it is organized. Software is typically a collection of documents.

2. Hardware: the buildings, vehicles, equipment, and materials of which the system is comprised.

3. Environmental conditions: the physical, economic, political and social factors within which the software, hardware, and liveware operate.

4. Liveware: the human beings involved with the system.

These system dimensions and the relationships between them comprise the basis of Edward's "SHEL Model" which is depicted in Figure 1.
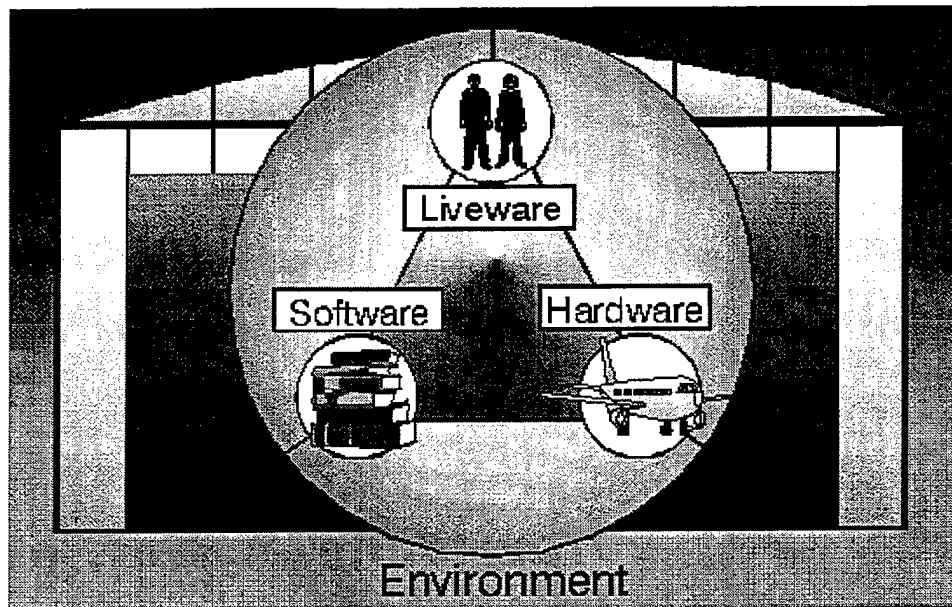
Figure 1: SHEL Model of System Design

The main assumption of the "SHEL Model" is that the system will fail when a failure occurs in any one of the four dimensions or in the connections between them. Edwards (1988) asserts that people are rarely the sole cause of accidents; but rather, accidents are caused by the interaction of several factors (Shappell and Wiegmann, 1997). The "SHEL Model" is a substantial departure from the commonly held belief that accidents are caused by single events (Edwards, 1981). The "SHEL Model" provides a method to describe systems, identify potential areas for concern within a system, and provide a general framework for accident investigation.

C. ACCIDENT INVESTIGATION

Understanding systems and the environment in which they operate provides a sound basis for accident investigation because when accidents occur they occur within their industrial and organizational context (Wagenaar, Groeneweg, and Hudson, 1994). The accident investigation process initially involves a retrospective analysis of past accidents to identify and focus upon areas of probable high risk. During this phase of the investigatory process, archival data are used to identify clusters of causal factors associated with the accident. These clusters are then used to help focus future safety efforts whose goal it is to recommend effective interventions that decrease the incidence of mishaps (McElroy, 1974).

Unfortunately, the perceptions of individual accident investigators can confound the goals of an accident investigation (Benner, 1982). Furthermore, despite the large number of accidents investigated, no generally accepted method of investigation exists (Benner, 1975). Accident investigators need to have well-defined objectives and a conceptual framework within which to work. Unless models of accident causation aid investigators in their analysis and serve

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as potential predictors of future accident scenarios, their usefulness will be limited (Hale, Stoop, and Hommels, 1990).

D. ACCIDENT REPORTING

Accident reports have traditionally focused on frequencies of occurrence and observations per unit time. However, frequencies and rates alone do not provide a sound basis to understand accidents (Brown, 1990a). A typical accident report consists of a narrative describing the accident accompanied by supporting documentation. The conventional process of reporting accidents varies in scope, depth, quality, objectivity, and suffers from inconsistencies and varying degrees of completeness (Edwards, 1981). In addition, human factors information concerning accidents is often not present because the traditional reporting format does not typically capture this class of variables (Adams, Barlow, and Hiddlestone, 1981).

Accident reports can aid in the determination of cause and the prevention of accidents only if the methods used to collect, classify, and record data are accurate and reliable. Accident reports are most useful when the information they contain is free from bias, is

based on the potential severity or frequency of occurrence, and is easily extractable (Adams and Hartwell, 1977).

Chapanis (1962) finds three elements essential for a good accident reporting system: properly trained investigators, a good accident report form, and centralized facilities for handling reports. Two of the most important functions of accident reporting systems are first, to prevent future accidents and second, to lessen the severity of the accidents that do occur (Brown, 1990b). Unfortunately, many accident-reporting methods do not meet these two design goals; instead, they tend to evolve without proper and coherent design objectives (Adams and Hartwell, 1977; Mayer and Ellingstad, 1992). This nonsystematic process causes subsequent data analysis to be very difficult (Primble and O'Toole, 1982) because the research design typically employed in analyzing the data generated by this process has been:

1. to gather data on past accidents within a population;

2. to divide the sample into groups with and without accidents;

3. to obtain measurements of individual characteristics on all subjects;

4. to statistically compare the measures for the two groups; and finally

5. to identify whether the two groups are significantly different, thereby concluding that the differential characteristic is strongly associated with accidents.

Many studies have used this general approach, but, the conclusions based on it are suspect. (Hale and Hale, 1972, Hansen, 1988; and Shaw and Sichel, 1971; as cited by Hansen 1989, p.81)

The outcome of an analysis based on this conventional method is suspect because the variable identified as a causal factor may not actually be responsible for the findings. Rather, the variable may be correlated to an unknown third variable which itself is the causal agent. However, over the past decade the tools available for reporting accidents have been refined and are now beginning to support more rigorous and structured methods of analysis (Leplat, 1989; Malaterre, 1990; Reason, 1990; Smith, 1997). The capacity of the accident report to provide data capable of distinguishing between causal and correlative variables determines the utility of possible interventions (Hill, Byers, Rothblum, and Booth, 1994).

E. ACCIDENT CAUSATION

1. Theory

There are several theories of accident causation whose objectives are to determine how accidents occur. Models of accident causation based on these theories attempt to predict and prevent accidents (Goetsch, 1996). Which theory is most useful is contested, but the predominant theme across all of them is that a chain-of-events culminates in an event called an "accident" (Grenier, 1997).

"Domino Theory" captures the essence of chain-of-event theories. "Domino Theory" suggests that accidents can be viewed as a five step sequence (Department of the Navy, 1997b).

1. Safety and Management: This is a supervisory problem.

2. Basic Causes: This includes human factors, environmental factors, or job related factors.

3. Immediate Cause: This includes substandard practices and conditions.

4. Accident: This typically is a result of falls or the impact of moving objects.

5. Personal injury and property damage: This includes lacerations, fractures, death, and material damage.

Effective intervention within the "Domino Theory" framework involves removing any of the first three "dominos" to prevent accidents, injury, and damage.

2. The Reason Model

Reason (1990) developed a model of accident causation using the principles of "Domino Theory." This model of accident causation was largely the result of a comprehensive study of catastrophic failures of complex technical and industrial systems. Some of the catastrophic failures examined included the U.S. Space Shuttle Challenger explosion, the Soviet nuclear reactor meltdown in Chernobyl, and the release of deadly gas by Union Carbide in Bhopal, India. Reason's model is comprised of three parts: the organizational process, task and environmental conditions, and individual unsafe acts. This model has been widely used for analyzing the role of management policies and procedures and the actions of individuals (Sargeant and Cavenagh, 1994). This model considers the errors people make the result of a chain-of-events as depicted in Figure 2.

INADEQUATE DEFENSES

ACTIVE FAILURES
&
LATENT FAILURES

UNSAFE ACTS

ACTIVE FAILURES

PSYCHOLOGICAL PRECURSORS OF UNSAFE ACTS

LATENT FAILURES

LINE MANAGEMENT DEFICIENCIES

LATENT FAILURES

FALLIBLE DECISION

LATENT FAILURES

INTERACTIONS WITH LOCAL EVENTS

ACCIDENT

Limited Window of Accident Opportunity
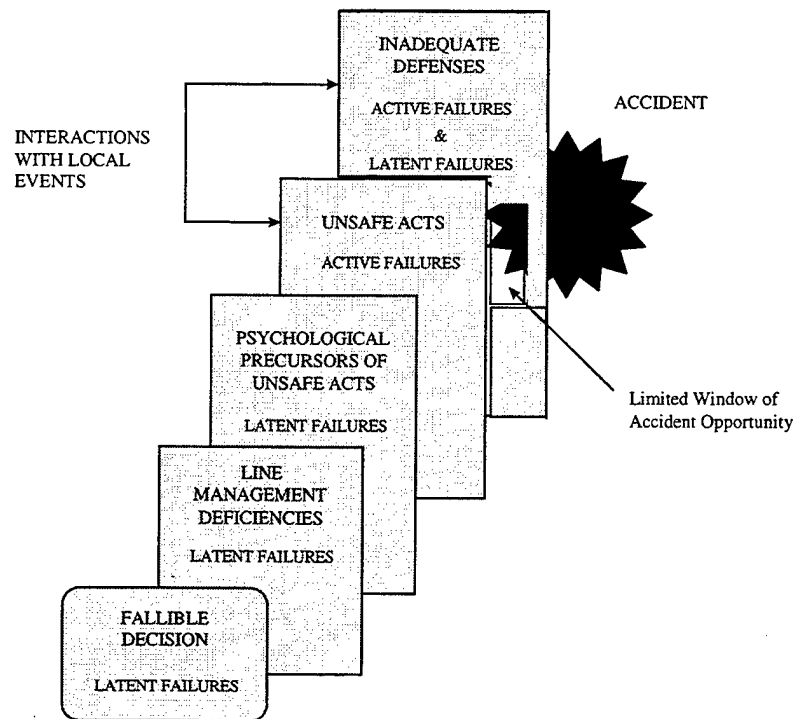
Figure 2: Reason's Accident Causation Model

Reason's model of accident causation examines accidents within the context of the organization in which they occur. Organizational actions that may contribute to mishaps are comprised of managerial decisions or actions that interact with environmental factors and individual unsafe acts to cause an accident (Reason, 1991). Unsafe acts that contribute to accidents are either *errors* or *violations. Errors* and *violations* are mediated by different psychological. mechanisms (Reason, Manstead, Stradling, Baxter, and Campbell,

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1990). Reason (1990) describes this differentiation as follows: "*Violations* require explanation in terms of social and motivational factors, whereas *errors* in the form of *slips*, *lapses*, and *mistakes* may be accounted for by reference to the information-processing characteristics of the individual (p.1315)." In general, this model illustrates how a combination of managerial decision-making, failures in technical expertise, and distorted communication increases the likelihood of a crisis in an organization (Smith, 1995).

Reason (1995) notes that, despite the differences in many disasters "…the root causes of these accidents have been traced to latent failures and organizational *errors* arising in the upper echelons of the system in question (p.1708)." The common elements of any accident which occurs in an organization include latent failures, local factors, active failures, and inadequate or absent defenses. Sargeant and Cavenagh (1994) define these elements as:

1. <u>Latent failures</u>: arising mainly from management decisions or actions whose repercussions may only become apparent when they combine with local triggering factors to breach the system's defenses. These latent failures are normally present well before the onset of a recognizable accident sequence, and may have remained unnoticed within the system for a considerable time.

2. <u>Local factors</u>: these are task, situational and environmental factors which directly influence performance in the workplace. Deficiencies in these factors can promote the occurrence of unsafe acts.

3. <u>Active failures</u>: are those *errors* or violations having an immediate adverse effect. These unsafe acts are typically associated with operational personnel.

4. <u>Inadequate or absent defenses</u>: which failed to identify and protect the system against technical and human failures arising from the three previous elements.

Accidents examined within an organizational context yields a more comprehensive understanding of the underlying accident process.

Within this organizational context, mistakes can be partitioned into two categories: mistakes caused by the lack of expertise and mistakes caused by a failure to actually apply expertise. Moreover, the organizational framework holds that the basis for these mistakes often remain inactive until they are activated by a "trigger event" (Smith, 1997). Psychosocial or managerially-related organizational features, when cojoined with seemingly unrelated and improbable events, can manifest their union in, yet again, an even more improbable event called an "accident." Reason (1990) contends that the focus of any intervention strategy must consider this conjunction between context and acts, which taken

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together, he calls *latent conditions*. Latent conditions are organized along seven general failure modes, which are shown in Table 1.

Table 1: Latent Condition General Failure Types

Modes of Action	Modes of Failure
Goal	Incompatible Goals
Organize	Inappropriate Structure
Manage	Communications Poor Planning Inadequate Control and Monitoring
Design	Design Failures
Build	Unsuitable Materials
Operate	Poor Operating Procedures Poor Training

Maintain	Poor Maintenance
	  Scheduling
	Poor Maintenance
	  Procedures
	Inadequate Regulation

Latent conditions are a primary key in comprehending the underlying causes of accidents because *latent conditions* are the result of decisions made by individuals who are not in direct control of the system (Zotov, 1996). In general, these individuals are not front-line operators, but are maintenance personnel,

construction workers, and managers associated with the system. *Active failures* on the other hand are those which are typically produced by front-line operators of the system (Grenier, 1997). *Active failures* differ from *latent failures* in that the person operating the system is responsible for causing them. Latent conditions and active failures both result from unsafe acts.

Reason's (1990) "Model of Unsafe Acts" differentiates *unsafe acts* into two primary categories, *intended* and *unintended*. Figure 3 depicts the "Model of Unsafe Acts."
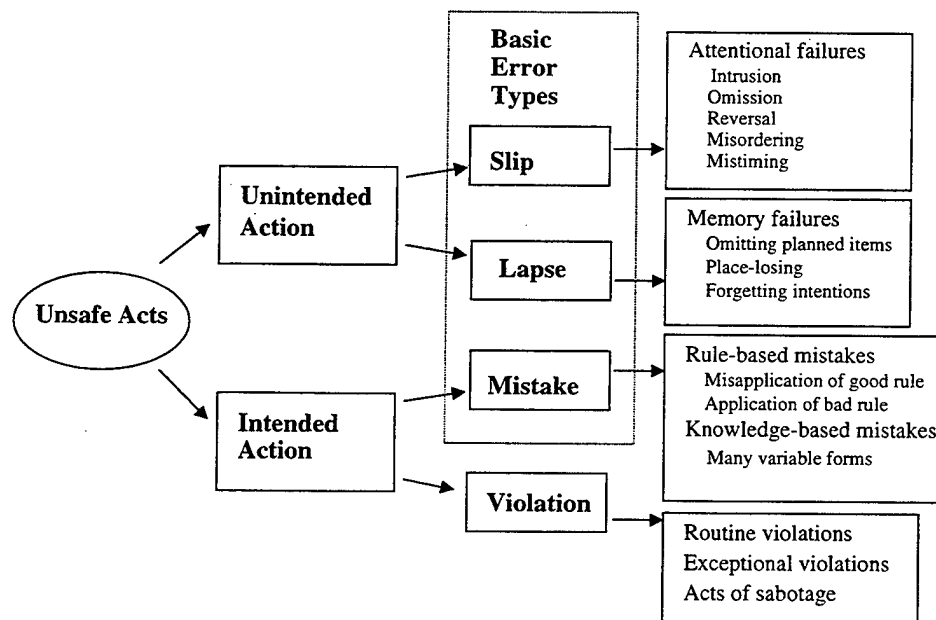
Figure 3: Psychological Varieties of Unsafe Acts

This model initially classifies the act according to whether it was *intended* or *unintended* and then distinguishes *errors* from *violations*. *Unintended acts*

include *slips* that are the performance of an action that was not what was intended (Norman, 1981), and *lapses* that are due to memory failures (Reason, 1990). *Intended actions* included *mistakes* and *violations*. *Mistakes* occur when previously learned procedures or rules are misapplied unintentionally and *violations* are the willful disregard of established policy or procedures.

Reason's model provides a framework through which the cause of accidents can be studied. In fact, this model has been widely used as a basis to understand the causes of accidents, but it does not provide a comprehensive basis for that analysis (Shappell and Wiegmann, 1997; Zotov, 1996). Wiegmann and Shappell (1997) argue that the structure of Reason's "Model of Unsafe Acts" needs to be expanded and applied to *unsafe conditions of the operator and unsafe supervision*. Their resulting taxonomy of unsafe operations, which evolved into the Human Factors Accident Classification System (HFACS), identifies both *active* and *latent* human errors within three general categories: *unsafe acts, unsafe conditions of the operator*, and *unsafe supervision*.

3. The Human Factors Accident Classification System

a. Overview

The Human Factors Accident Classification System (HFACS) taxonomy was developed by Wiegmann and Shappell (1997) to help analyze Naval Aviation accidents. HFACS incorporates features of Bird's (1974) "Domino Theory," Edward's (1972) "SHEL Model," and Reason's (1990) "Unsafe Acts Model." In particular, using Edward's (1972) "SHEL Model," failures are partitioned into one of three levels of human-component failure and its associated organizational environment. Figure 4 shows the relationship of the three levels of human-component failure, which include:

- Level 1: unsafe supervision.

- Level 2: unsafe operator conditions.

- Level 3: unsafe acts of the operator.

These human-component failure categories enable an analyst to identify failures at each of the three levels historically related to accidents. This classification can then be used to target the most appropriate intervention.
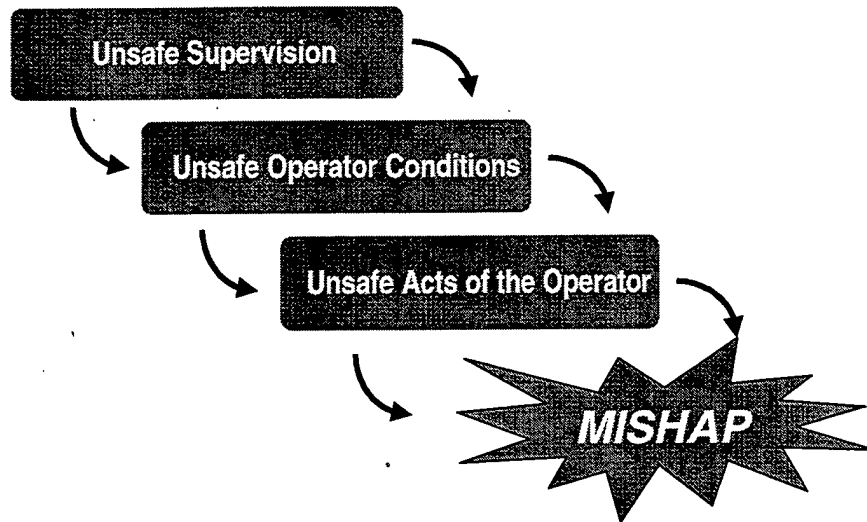
Figure 4: Levels of Human-Component Failure

b. Organizational Influences

Human-component failures are always affected by organizational influences. HFACS classifies organizational influences into three broad areas: *resource management*, *organizational climate*, and *operational processes*. Table 2 provides a summary of the HFACS classifications involving organizational influence.

Table 2: Classification of Organizational Influence

Resource Management	Organizational Climate	Operational Processes
Human	Structure	Operations
Monetary	Policies	Procedures
Equipment &Facility	Culture	Oversight

Organizational influence refers to *latent failures* induced by upper-level management that directly affect all three levels of human-component failure. *Latent failures* are partitioned into three classes: *resource management*, *organizational climate*, and *operational processes*. *Resource management* includes human, monetary, and equipment resources; for example, failures induced by excessive cost cutting or lack of funding. *Organizational climate* refers to the prevailing culture within an organization. *Operational processes* include the formal methods by which things are accomplished in an organization (Shappell and Wiegmann, 1997).

c. Unsafe Supervision

Failures associated with *unsafe supervision* can be partitioned into two subsets. Those that are *unforeseen* and those that are *known* (Shappell and Wiegmann, 1997). *"Known" unsafe supervision* includes inadequate supervision, planned inappropriate operations, failure to correct known problems, and supervisory violations. Supervisory violations include circumstances in which front-line or middle-level management do not agree with stated policies or openly disparage supervisors. *Known unsafe supervisory* actions

often include situations in which the supervisor's intent may not be purposefully malicious, but simply imperious; that is, the supervisor may simply believe that "I know best."

"Unforeseen" *unsafe supervision* includes the failure to recognize unsafe operations, a lack of documentation, and inadequate design. Supervisors may have to manage several individuals who are completing tasks simultaneously. The workload imposed by this management condition can overwhelm a supervisor and diminish their situational awareness. Furthermore, supervisors will occasionally face unanticipated personal issues that adversely impact their overall effectiveness. Unanticipated equipment design problems or a lack of technical specifications, instructions, and regulations can also contribute to failures. Challenges such as these will always exist and will often contribute to the sequence of events leading to accidents. Table 3 provides a summary of the *unsafe supervision classification*.

Table 3: Classification of Unsafe Supervision

Known Unsafe Supervision	Unforeseen Unsafe Supervision

<u>Inadequate Supervision</u>
 	
    Failure to administer
      proper training
    Lack of professional
      guidance
 	
<u>Planned Inappropriate</u>
<u>Operations</u>
   Improper work tempo
 	
<u>Failed to Correct Known</u>
<u>Problem</u>
    Failure to correct
      inappropriate behavior
    Failure to correct
      Safety hazard
 	
<u>Supervisory Violations</u>
    Not adhering to rules
      and regulations
    Willful disregard for
      authority by supervisors
	<u>Failure to Recognize Unsafe</u>
	<u>Operations</u>
	    Loss of supervisory
	      Situational awareness
	    Unseen unsafe
	      Conditions/hazards
	    Unrecognized adverse medical
	      Conditions
	    Life changes (e.g. divorce,
	      Family, death, legal,
	      Financial, or personal
	      Problems)
	
	<u>Lack of Documentation</u>
	    Lack of technical specifica-
	      tions, instructions, regu-
	      lations, etc.
	
	<u>Inadequate Design</u>
	    Equipment design that
	      contributes to accident

Shappell and Wiegmann (1997)

d. Unsafe Conditions of the Operator

The *unsafe condition* and *unsafe acts* categories are closely related. *Substandard conditions of the operator* include adverse physiological states, adverse mental states, and physical or mental limitations. Operator errors manifest themselves as a function of increasing workload and can not be avoided, but adverse physiological states can greatly increase the likelihood of an accident and indeed, can be avoided (Groeger, 1990). The second category, adverse mental states, involves psychological or mental problems

affecting the operator. These states, such as overconfidence and complacency, deficient situational awareness, and fatigue-related problems induced by circadian dysrhythmia and general drowsiness must be considered by an investigator to provide a more complete understanding of failures (Lourens, 1990). The third category of *unsafe conditions of the operator* involves diminished physical or mental capabilities of the operator. This category also includes special aspects of the environment that can adversely impact performance; for example, the debilitating effects of a sensorially impoverished or satiated environment.

Substandard practices are partitioned into three categories: mistakes and misjudgments, crew resource mismanagement, and readiness violations. Mistakes and misjudgments often involve behaviors that do not violate existing rules and regulations, yet still impair job performance. These behaviors include poor dietary practices and overexertion while off duty. Crew resource mismanagement includes not working as a team, poor crew coordination, improper task briefing, and inadequate task coordination. Crew resource management focuses on individuals directly engaged in a group task. It does not include high-level management personnel. The

category of *substandard practices of the operator,* is *readiness violation.* A *readiness violation* is assumed when regulations regarding crew rest, alcohol consumption, or medications are not adhered to. Table 4 provides a general summary of the dimensions of unsafe condition of the operator.

Table 4: Classification of Unsafe Conditions of the Operator

Substandard Conditions	Substandard Practices

Adverse Physiological States
   Spatial disorientation
   Hypoxia
   Intoxication
   Visual illusions
   Physical fatigue
   Motion sickness
   Medical illness
	Mistakes and/or Misjudgments
	   Poor dietary practices
	   Overexertion while off duty

Adverse Mental States
   Loss of situational
     awareness
   Circadian dysrhythmia
   Complacency
   Alertness (Drowsiness)
   Overconfidence
	Crew Resource Mismanagement
	   Not working as a team
	   Poor aircrew coordination
	   Improper briefing before a
	     Mission
	
	Readiness Violation
	Not adhering to regulations
	   regarding crew rest,
	   alcohol consumption, or
	   medications

Physical and/or Mental
Limitation
   Lack of sensory input
   Limited reaction time
   Insufficient physical
     capabilities
   Insufficient intelligence	

Shappell and Wiegmann (1997)

e. Unsafe Acts of the Operator

The classification of *unsafe acts of the operator* is partitioned into *unintended* and *intended acts*. *Intended unsafe acts* are defined as acts in which an operator deviates from a plan and is unaware of the deviation. A deviation from planned action is due either to a failure in execution or a failure of memory. Both failures occur at the skill-based level of processing. Failures in execution are referred to as *slips* and these include errors of intrusion, omission, reversal, misordering, and mistiming. *Slips* are due to attentional *lapses*. Memory failures typically involve the omission of planned items including losing ones' place and forgetting intentions. Operators are usually unaware of *slips* and *lapses*.

Intended unsafe acts are either *mistakes* or *violations*. *Mistakes* include the misapplication of a good rule or the application of a bad rule. *Mistakes* may be knowledge-based errors that involve an inaccurate or incomplete mental model of the problem space. In contrast, knowledge-based errors are the result of an operator having insufficient familiarity with the system or task. Individuals who are not experts in their field

or experts not fully familiar with a new system are prone to errors of this type.

The HFACS taxonomy of *unsafe acts* defines *violations* as intended actions that may be either routine or exceptional. *Routine violations* are habitual departures from rules and regulations that are generally condoned by management. These *violations* are commonly viewed by operators and management as being acceptable departures from rules or regulations. Table 5 provides a summary of this classification (Shappell and Wiegmann, 1997).

Table 5: Classification of Unsafe Acts of the Operator

Unintended Actions	Intended Actions

<u>Slips: Attention Failures</u>
  Intrusion
  Omission
  Misordering
  Reversal
  Mistiming
	<u>Mistakes</u>
	  Rule-based
	  Misapplication of a good rule
	  Application of a bad rule
	  Knowledge-based
	  Inaccurate or incomplete mental
	    model of the problem space

<u>Lapses: Memory Failures</u>
  Omitting
    planned items
  Place-losing
  Forgetting
  Intentions
	<u>Violations</u>
	  Routine
	  Habitual departures from rules and
	    regulations condoned by management
	  Isolated departures from rules and
	    regulations not condoned by
	    management
	  Exceptional

Shappell and Wiegmann (1997)

F.   THE HFACS MAINTENANCE EXTENSION

The *HFACS Maintenance Extension* taxonomy was used in the present work to classify causal factors that contribute to maintenance related mishaps. This addition to the HFACS consists of four broad human error categories: *Supervisory Conditions*, *Working Conditions*, *Maintainer Conditions*, and *Maintainer Acts* (see Figure 5).
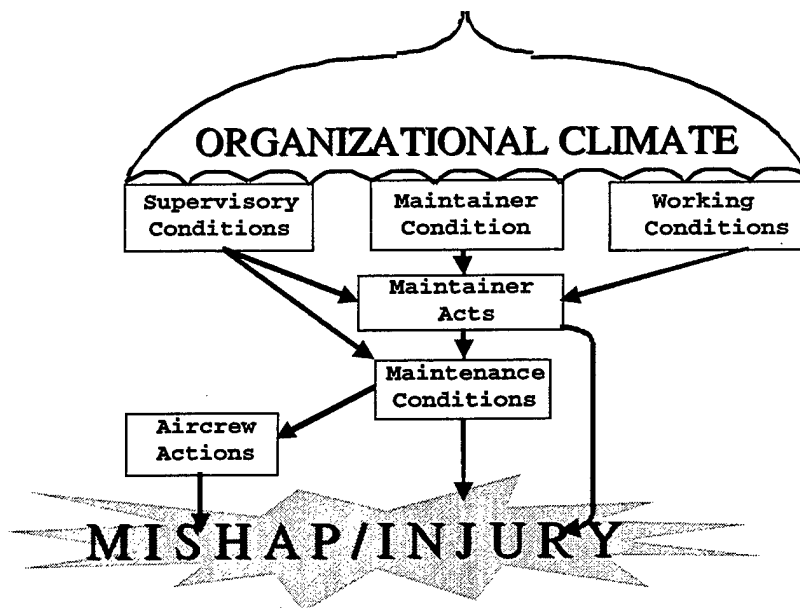
Figure 5: HFACS Maintenance Extension

Supervisory Conditions, *Working Conditions*, and *Maintainer Conditions* are *latent conditions* that can impact a maintainer's performance and can contribute to an *active failure*. A maintainer's *active failure* may lead directly to a mishap or injury; for example, a

maintainer who runs a forklift into the side of an aircraft. The *active failure* could also become a *latent condition* with which the aircrew would have to accommodate in flight. *Maintenance Conditions* can directly lead to mishap or injury through no fault of the aircrew; for example, an improperly rigged landing gear that collapses on touchdown.

Maintenance Conditions can also cause an emergency that the aircrew must ultimately accommodate in flight. The end result would at least be minor damage or injury or in the worst case, could lead to loss of an aircraft and loss of life; for example, a fire caused by an over-torqued hydraulics line that ruptures in flight. It is important to note that *Supervisory Conditions* related to aircraft design for maintainability, prescribed maintenance procedures, and standard maintenance operations could be inadequate and lead directly to a *Maintenance Condition*. The three orders of maintenance error — first order, second order, and third order — reflect a decomposition of the error type from a molar to a micro perspective. These three orders are summarized in Table 6.

Table 6: HFACS Maintenance Extension Categories

First Order	Second Order	Third Order
Supervisory Conditions	Unforeseen	Unrecognized Unsafe Operations Inadequate Documentation Inadequate Design
	Squadron	Inadequate Supervision Planned Inappropriate Operations Failed to Correct Problem Supervisory Violation
Maintainer Conditions	Medical	Mental State Physical State Physical/Mental Limitation
	Crew Resource Management	Communication Assertiveness Adaptability/Flexibility
	Personal Readiness	Preparation/Training Qualification/Certification Violation
Working Conditions	Environment	Lighting/Light Exposure/Weather Environmental Hazards
	Equipment	Damaged Unavailable Dated/Uncertified
	Workspace	Confining Obstructed Inaccessible
Maintainer Acts	Error	Attention Memory Rule/Knowledge Skill
	Violation	Routine Exceptional

Schmidt (1998)

The classification of latent *Supervisory Conditions* that can contribute to an active failure includes both unforeseen and squadron error types. Examples of situations potentially leading to *unforeseen supervisory conditions* include:

- An engine that falls off an engine-stand during change-out evolution due to an unforeseen hazard of a high sea state (Unrecognized Unsafe Operation).

- A maintenance plan that omits a necessary step in a maintenance procedure, such as leaving out an o-ring that causes a fuel leak (Inadequate Documentation).

- The poor layout of system components that do not permit direct observation of maintenance being performed (Inadequate Design).

Examples of situations potentially leading to squadron *Supervisory Conditions* include:

- A supervisor who does not ensure that maintenance personnel are wearing required personal protective gear (Inadequate Supervision).

- A supervisor who directs a maintainer to perform an operation without considering associated risks, such as driving a truck through an aircraft hanger (Planned Inappropriate Operations).

- A supervisor who neglects to correct maintainers who routinely bend the rules when they perform a routine check (Failed to Correct Problem).

- A supervisor who willfully orders a maintainer to wash an aircraft without proper safety gear (Supervisory Violation).

Latent Maintainer Conditions that can contribute to an active failure include medical, crew resource management, and personal readiness. Examples of maintainer medical conditions include:

- A maintainer who has a marital problem and can not focus on a maintenance action being taken (Mental State).

- A maintainer who worked 20 hours straight and suffers from mental and physical fatigue (Physical State).

- A maintainer who is short and can not visually inspect aircraft before it is prepared for a catapult launch (Physical Limitation).

Examples of maintenance crew resource management conditions include:

- A maintainer who leads an aircraft being taxied into another parked aircraft because improper hand signals were used (Communication).

- A maintainer who performs a maintenance action not in accordance with standard maintenance procedures because the maintainer was overly submissive to a superior (Assertiveness).

- A maintainer who dismisses an apparent downing discrepancy to meet the flight schedule (Adaptability).

Examples of maintenance personal readiness conditions include:

- A maintainer working on an aircraft although the maintainer did not review proper training material (Training).

- A maintainer engages in a procedure that they are not qualified to perform (Qualification).

- A maintainer intoxicated on the job (Violation).

Latent Working Conditions such as poor environmental factors, inadequate equipment, and uncomfortable workspaces all impact maintainer acts. For example, a maintainer who must work in a confined workspace or on the deck of an aircraft carrier during bad weather and heavy seas will likely perform poorly. Similarly, a maintainer who unknowingly uses outdated

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maintenance publications or damaged ground support equipment can adversely impact the quality of the maintenance. *Working Conditions* include the physical environment in which the maintainer works and the tools they use in the course of their work.

Active failures in the form of *Maintainer Acts* include both *errors* and *violations*. *Active failure* can directly cause damage and injury, or lead to a *latent* maintenance condition. *Active failures* include:

- A maintainer who misses a hand signal and backs a forklift into an aircraft (Attention).

- A mechanic who may be very familiar with a certain sequence of multiple steps that must be taken, but may inadvertently reverse the ordering of two of the steps within the sequence and unwittingly contribute to an accident (Memory).

- A maintainer who inflates an aircraft tire to a pressure required for a different type of aircraft tire (Rule).

- A mechanic who roughly handles a delicate engine valve and breaks a piece off (Skill).

The HFACS Maintenance Extension defines *violations* as intended actions that may be either routine or exceptional. *Routine violations* are practices that are habitual departures from rules and regulations that are generally condoned by management. These *violations* are commonly viewed by operators and management as being acceptable departures from rules or regulations. An

example of a routine violation might include a situation where a forklift operator knowingly exceeds a speed limit in an aircraft hanger by three to five miles per hour, and management is aware of this violation yet does not intervene. In comparison, an exceptional violation would include a situation where the forklift operator exceeds the aircraft-hanger speed limit by twenty miles per hour.

G.   SUMMARY

A human error taxonomy is a tool used to evaluate accidents. The HFACS Maintenance Extension is a taxonomy designed specifically for the analysis of aviation maintenance-related mishaps. This taxonomy was developed within the framework of the HFACS taxonomy that proved useful in the analysis of pilot error associated with aviation mishaps. Furthermore, the HFACS Maintenance Extension is based upon established theories of human error and system design. Accordingly, the HFACS Maintenance Extension was chosen for use in the present study to aid in the analysis of Naval Aviation MRMs.

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III. METHODOLOGY

A. RESEARCH APPROACH

This research involved the adaptation and analysis of an existing accident mishap database maintained by the U.S. Naval Safety Center. This mishap database includes all Naval Aviation Class A, B, and C Flight, Flight-Related, and Aircraft Ground mishaps. The database consists of data taken from mishap investigation reports (MIRs) submitted by Aircraft Mishap Boards (AMBs). Each MIR follows a prescribed format and includes a brief summary of the mishap event, characteristics of the mishap, and a summary of causal factors (Department of the Navy, 1997b).

The analysis of this data consists of four phases. The first phase examines the operational environment in which the mishaps used in this study occurred, then it describes the mishaps themselves. The second phase develops and evaluates mathematical models that represent the underlying mishap arrival process. The third phase identifies and summarizes human errors associated with each mishap. The final phase presents cost savings estimates based on potential reductions of human error in aviation maintenance. The cost saving

estimates are based on the specific human errors associated with various maintenance actions and the mathematical models developed to represent them.

B.   DATA COLLECTION

The Naval Safety Center aviation mishap database was queried to identify all Naval Aviation MRMs. A total of 470 MRMs from FY90 through FY97 were obtained. Data included the mishap date, Type (e.g., FM, FRM, and AGM), Class (e.g., Class A, B, and C), associated casual factors, and the cost. Additionally, data were obtained from the Naval Safety Center and the Chief of Naval Air Warfare (N88) on the number of flight-hours flown per month, the number of fleet aircraft in operation per month, and the average age of those aircraft. Monthly totals of the mishaps were used and treated as point-event data to infer the data's pattern and properties. Causal factors associated with the mishaps were coded according the HFACS Maintenance Extension to account for the range of human error types.

C. DATA ANALYSIS

1. Data Tabulation

The occurrences of MRMs and associated error types, and additional relevant data were entered into a spreadsheet for subsequent analysis. Monthly totals of these data were calculated and served as the basis for this analysis.

2. Analysis

The frequency of mishaps by Class and Type were determined. Various mathematical models were fitted to the data to find the one that best fit it. Human errors associated with the mishaps were identified and an estimate of dollar savings resulting from the reduction of each error type was produced. Procedural and policy recommendations are based on these results.

IV. RESULTS

A. BACKGROUND

The rate of Naval Aviation MRMs of all Classes and Types per 100,000 flight-hours has generally decreased during FY90 through FY97. In particular, Figure 6 shows the number of Naval Aviation MRMs has decreased from an average of 3.1 mishaps for FY90-FY94 to an average of 1.7 for FY95-FY97. In addition, the MRM rate as a percentage of the overall Naval Aviation mishap rate has dropped 23 percent during this time-period. The MRM rate dropped from an average of 30 percent of total mishaps before FY95 to a subsequent average of 23 percent.
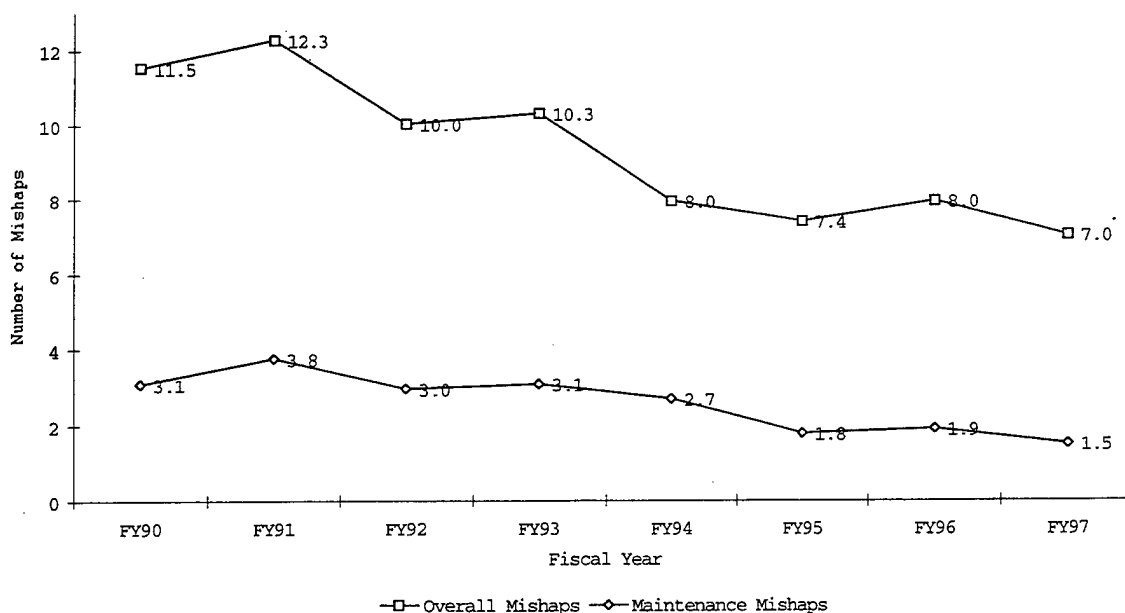
Figure 6: Naval Aviation Mishap and MRM Rates

From October 1989 through September 1997, Naval Aviation operated in an environment which had three significant trends: a reduction in the overall number of flight-hours flown, a reduction in the number of planes available, and an increase in the overall average age of the planes available. Figure 7 shows these trends.
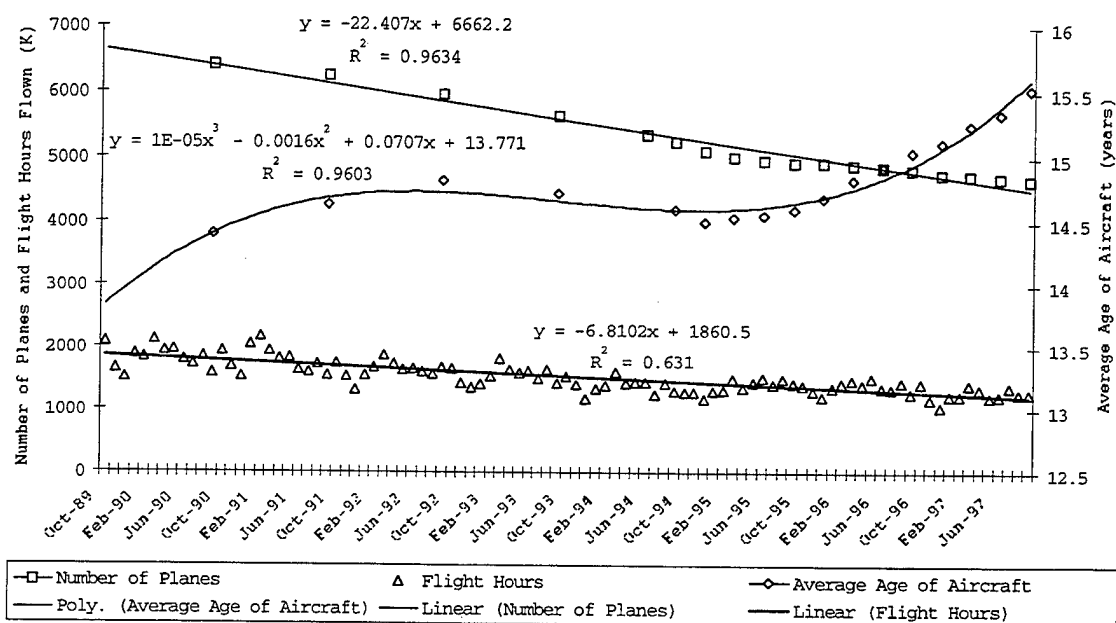
Figure 7: Trends in Naval Aviation

Historically, the number of flight-hours flown is considered a major factor in the analysis of aviation mishaps because increased flight operations increase maintenance requirements. Figure 8 shows that the number of MRMs per month increase as the number of flight-hours flown per month increase.

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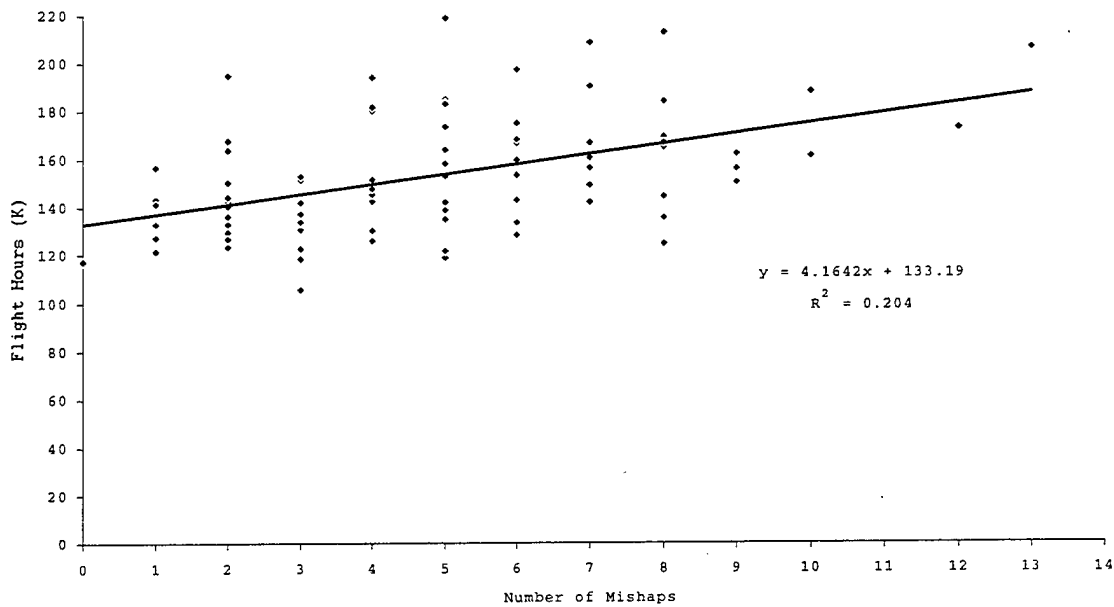
Figure 8: Flight-Hours Flown Versus Number of MRMs

Patterns in MRMs can be more clearly seen by examining them by Class and Type. Figure 9 reveals that MRMs are unevenly distributed across Class and Type and that Class C mishaps and Aircraft-Ground mishaps (AGMs) comprise the largest percentage of mishap Class and Type. Table 7 shows that nearly 50 percent of all the MRMs are Class C, Aircraft-Ground mishaps (AGMs) mishaps.
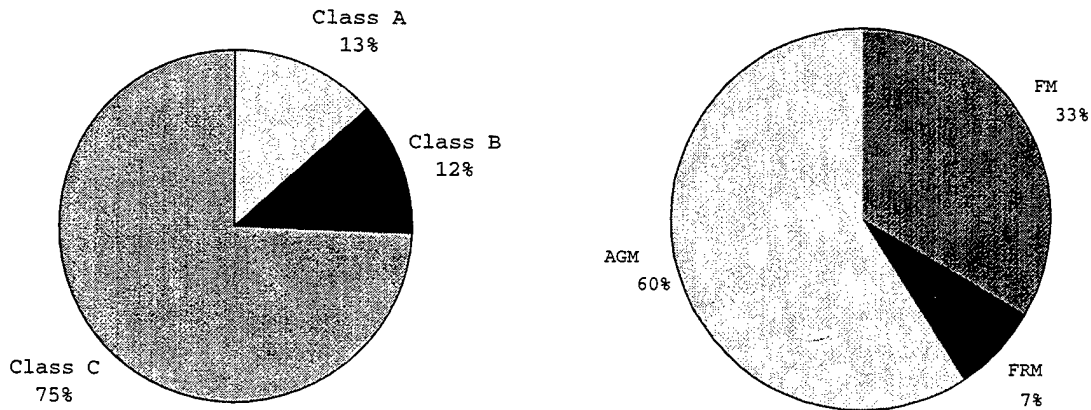
Figure 9: FY90-FY97 MRMs by Class and Type

Table 7: FY90-FY97 Maintenance-Related Mishaps

	Flight	Flight-Related	Aircraft-Ground	Total
Class-A	50	0	13	63
Class-B	17	6	34	57
Class-C	90	29	231	350
Total	157	35	278	470

Fifty-one people died in these mishaps: 40 were attributed to FMs and 11 to AGMs. In terms of direct financial costs, MRMs cost Naval Aviation over $800 million during the period under study; that is, from FY90 through FY97. Although Class A Flight mishaps make-up only 13 percent of all mishaps, Table 8 shows that they are the largest contributor to overall cost. Table 9 contains the average costs of MRMs by Class and Type for FY90 through 1997. Costs were normalized to FY98 dollars using aircraft procurement and weapons procurement inflation indices.

Table 8: FY90-FY97 Total MRM Costs (FY98$M)

	FM	FRM	AGM	Total
Class-A	796	0	3	799
Class-B	8	2	11	22
Class-C	6	2	9	16
Total	810	4	23	837

Table 9: FY90-FY97 Average MRM Costs (FY98$K)

	FM	FRM	AGM	Total
Class-A	16579	0	260	13537
Class-B	514	393	362	412
Class-C	164	56	43	59
Total	8261	116	91	2168

B. DATA EXPLORATION

The frequency with which accidents occur can provide valuable information to reveal the accident's underlying arrival process. Events, such as accidents, and their associated times of occurrence are point-event data. One analytic method for point-event data is to group the data into finite time intervals then evaluate their distribution. Figures 10 and 11 show the distribution of the 96 months of MRM data by Class and Type.
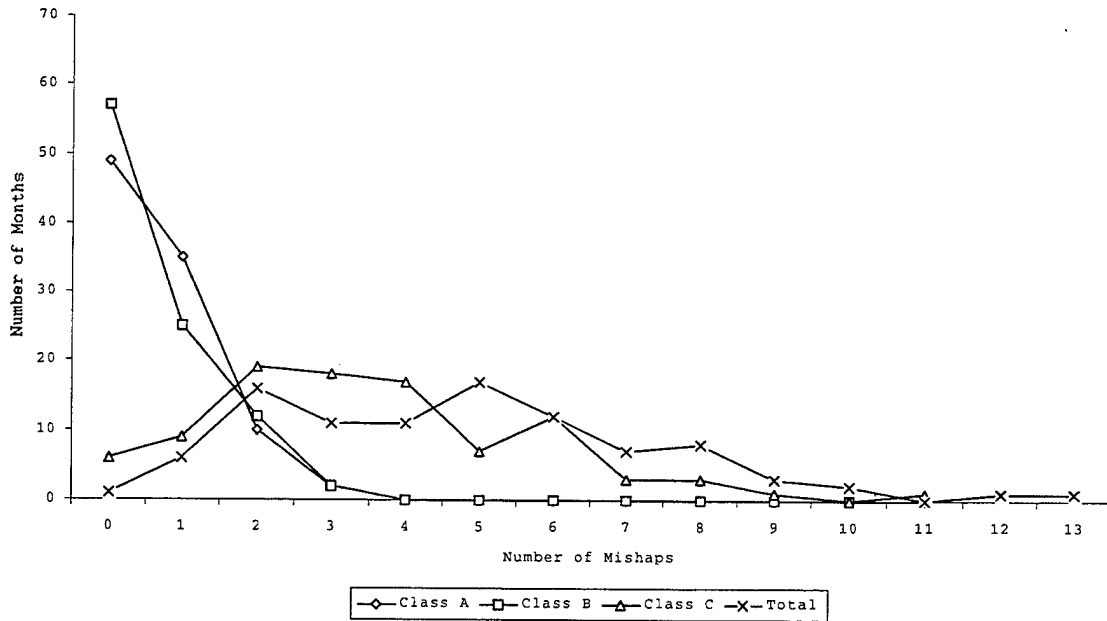
Figure 10: Distribution of Monthly Mishaps by Class
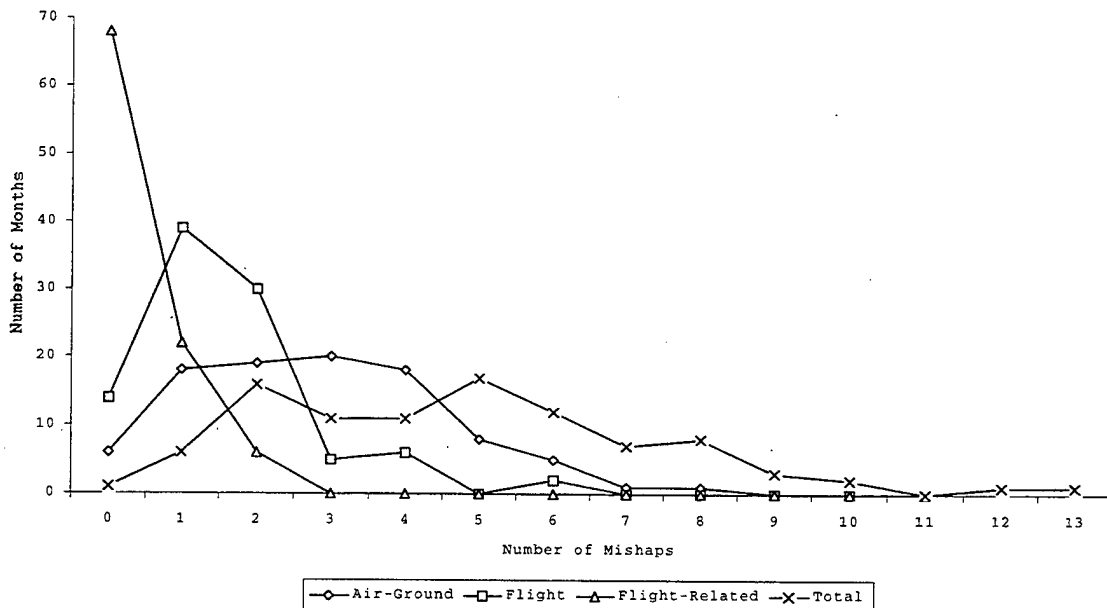
Figure 11: Distribution of Monthly Mishaps by Type

Data were grouped by month and fiscal year in this study. Table 10 shows the overall number of undifferentiated MRMs by month of occurrence. Tables of

the monthly numbers of MRMs partitioned by Class and Type are at Appendix A.

Table 10: Total MRMs by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	7	2	6	8	3	6	5	6	43
November	6	8	5	1	5	2	2	0	29
December	3	6	2	5	3	5	1	3	28
January	7	13	7	5	6	4	8	3	53
February	8	5	2	6	5	1	6	3	36
March	8	4	10	5	7	7	4	2	47
April	4	4	5	2	3	2	1	3	24
May	6	5	8	6	4	4	4	5	42
June	4	5	7	9	8	2	2	2	39
July	5	10	6	9	8	2	3	3	46
August	5	12	1	5	4	2	2	2	33
September	5	9	6	7	3	2	4	1	37
Total	68	83	65	68	59	39	42	33	457

General indications suggest there is an overall decreasing trend in MRMs. However, Figures 12 and 13 show that this overall-decreasing trend is primarily due to a drop in Class C mishaps, FMs, and AGMs. Class A, Class B, and FRMs remained constant during this same period.
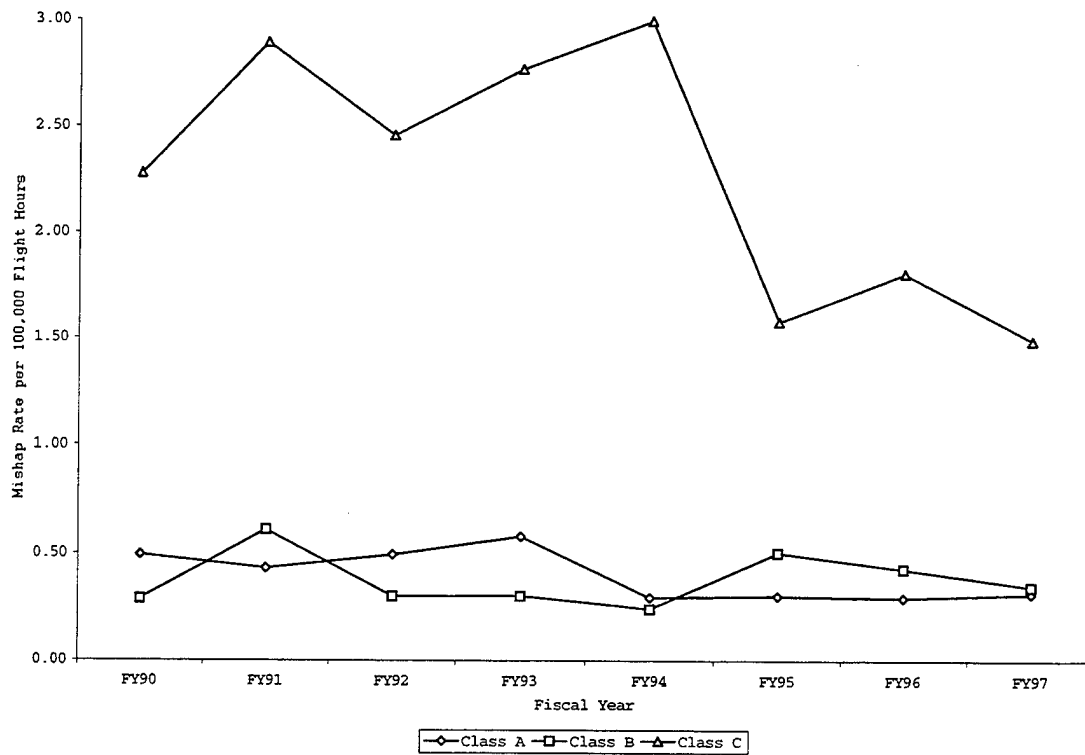
Figure 12: Mishap Rate by Class
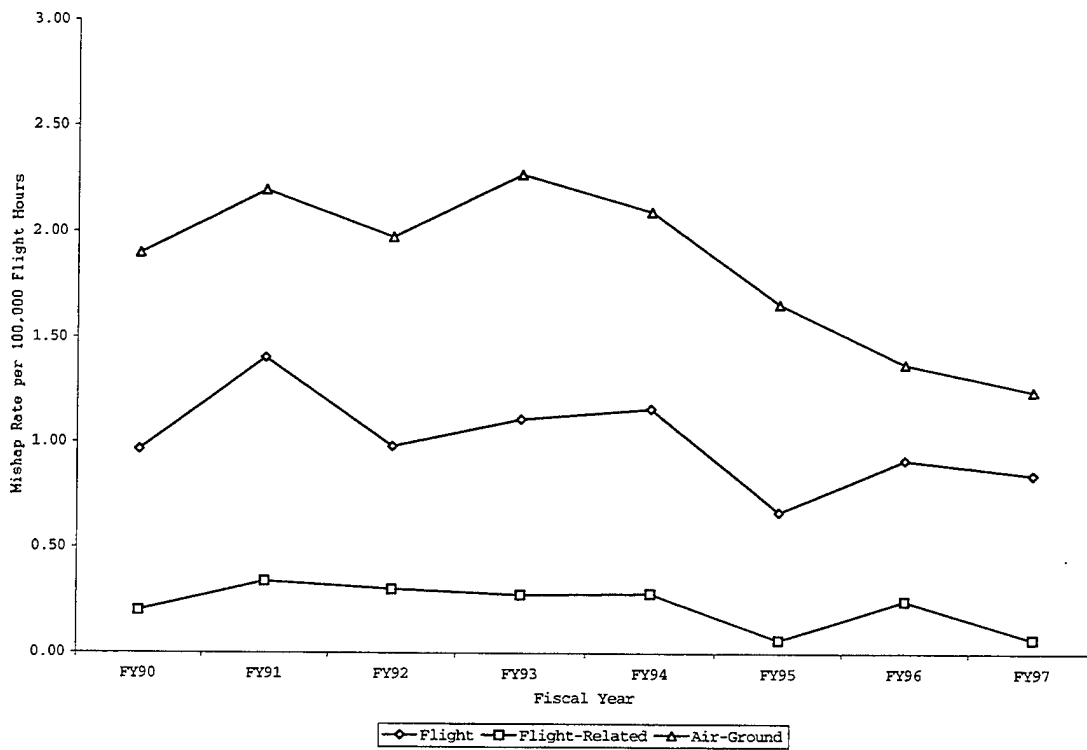
Figure 13: Mishap Rate by Type

C.   STOCHASTIC MODELING

Model fitting was used to reveal MRM's underlying arrival process. Gaver (1996) argues that if a model is considered successful it will describe similar patterns in future data. Furthermore, he specifies models for the occurrence of point event arrivals as relatively simple mathematical formulas, which are specified by one or two parameters inferred from the data.

Initial attempts to study the underlying mishap process focused on the identification of suitable, simple mathematical models that summarize the mishap data. The models considered included the Poisson process with homogenous and non-homogenous piece-wise constant rates, a moving average estimator, and a variable Poisson process. The specific question posed was: "Does strong evidence exist that the distributions of the number of arrivals per unit of time differ from one another?"

Gaver (1996) reasons that "… models are not supposed to be perfect representations of the data sets to which they are fitted, but to represent the situation of concern well enough to be useful (p.3)." The models considered were tested using a modified denominator-free

χ^2 statistical test, which is superior to the classical χ^2 statistical test when the data values are small and include zeros (Freeman and Tukey, 1950). It was determined on an a priori basis that models with probabilities lower than 0.05 would not be used.

The variable Poisson process model was found to be most adequate statistically in describing the MRMs. The variable Poisson process model is a method to generate an estimator based on a function fitted to historical data (Cox and Lewis, 1968). A curve is fitted to the historical data and is used to predict the mean of the hypothetical Poisson process that produces the failures. The variable Poisson process model was the simplest model found to be suitable based on initial evaluation and subsequent cross-validation. Therefore, this model forms the basis for subsequent analysis of the MRMs. Appendix B details alternative models that were rejected.

The variable Poisson process model generates monthly hypothetical MRM means for the mishap data. The value at some month t is assumed to come from a Poisson process with mean λ_t, and further it is assumed that λ_t follows the exponential decay equation $\lambda_t = a * \exp(-b * t)$. The

values a and b are estimated by maximum likelihood. The likelihood function is given by

$$L(a,b) = \exp(-\sum_{t=1}^{n} a*\exp(-bt)) - \prod_{i=1}^{t} [a*\exp(-bt)]^{Y_t} \ .$$

where Y_t is the number of mishaps at time t. The log likelihood is

$$\ell = -\sum_{t=1}^{n} a*\exp(-bt) + \sum_{t=1}^{n} Y_t*\log[a*\exp(-bt)] \ .$$

This yields the derivatives

$$\frac{\partial\ell}{\partial a} = -\sum_{t=1}^{n} \exp(-bt) + \sum_{t=1}^{n} \frac{Y_t*\exp(-bt)}{a*\exp(-bt)}$$

$$= -\sum_{t=1}^{n} \exp(-bt) + \sum_{t=1}^{n} \frac{Y_t}{a} \ = \sum_{t=1}^{n} \left[\frac{Y_t}{a} - \exp(-bt)\right]$$

and

$$\frac{\partial\ell}{\partial b} = -\sum_{t=1}^{n} a(-t)*\exp(-bt) + \sum_{t=1}^{n} \frac{Y_t*a(-t)*\exp(-bt)}{a(-t)*\exp(-bt)}$$

$$= \sum_{t=1}^{n} at*\exp(-bt) - \sum_{t=1}^{n} tY_t \ = \sum_{t=1}^{n} \left(t*[a*\exp(-bt) - Y_t]\right) \ .$$

An S-plus computer program was developed to generate the values of $\hat{a}$ and $\hat{b}$ that makes the sum

$$\left(\sum_{t=1}^{n} \left[\frac{Y_t}{\hat{a}} - \exp(-\hat{b}t)\right]\right)^2 + \left(\sum_{t=1}^{n} \left(t*[\hat{a}*\exp(-\hat{b}t) - Y_t]\right)\right)^2$$

equal to zero. This computer program can be found in Appendix C.

Once the equation that meets the criterion of least
squares is obtained; the predicted values at each month
t are calculated and compared to the data. Figure 14
presents the equation fitted to the total MRM data.
Figures for mishap Class and Type can be found in
Appendix D.
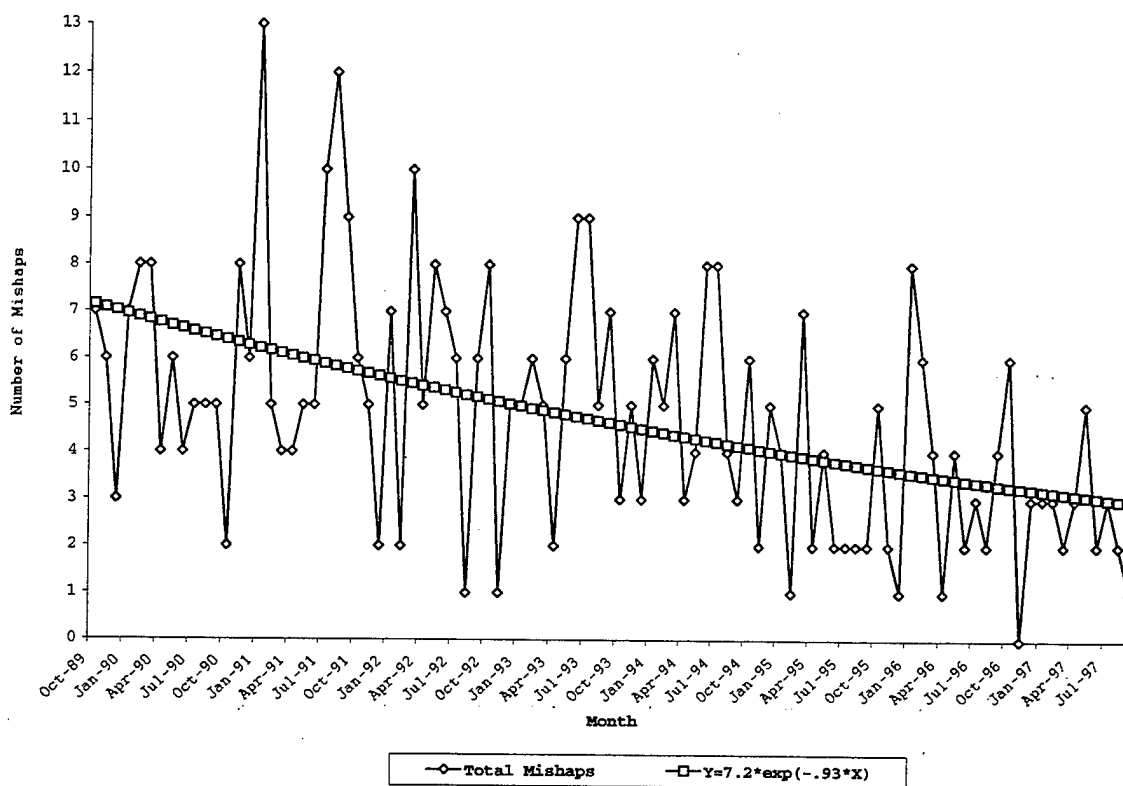
Figure 14: Variable Poisson Process for Total MRMs

The distribution of the number of MRMs for each
month is assumed Poisson with mean λ_m. The estimate of
λ_m is $\hat{\lambda}_t = \hat{a} * \exp(-\hat{b} * t)$. The modified denominator-free χ^2
test was used to determine the suitability of the

estimates. This goodness of fit test compared

$$\sum_{i=1}^{96} \left(\sqrt{m_i} + \sqrt{m_i+1} - \sqrt{4*\hat{\lambda}_t+1} \right)^2 \text{ to a } \chi_{95}^2 \text{ obtaining a probability,}$$

$P\{\chi_{95}^2 \geq \hat{\lambda}_t\}$. Table 11 shows the values of $\hat{a}$ and $\hat{b}$ that were calculated, the probabilities obtained, and the suitability of the models.

Table 11: Variable Poisson Process Model Validation

Mishap Classification	$\hat{a}$	$\hat{b}$	$P\{\chi_{95}^2 \geq \hat{\lambda}_t\}$	Suitability
Flight	2.3	0.93	0.962	Not Unusual
Flight-Related	0.7	0.91	0.999	Not Unusual
Aircraft-Ground	4.3	0.85	0.725	Not Unusual
Class A	1.0	1.43	0.989	Not Unusual
Class B	0.7	1.08	0.940	Not Unusual
Class C	6.9	0.46	0.079	Not Unusual
Total	7.2	1.38	0.327	Not Unusual

The variable Poisson process model goodness of fit test results are above the 0.05 threshold initially established for the suitability of the models. Therefore, the variable Poisson process model adequately statistically describes FMs, FRMs, AGMs, Class A, Class B, and Class C, and total mishaps. An assessment of the model for predicting MRM data was tested using additional MRM data. Table 12 contains this new mishap data.

Table 12: October 1997 - March 1998 Monthly MRMs

Mishap Classification	OCT	NOV	DEC	JAN	FEB	MAR
Flight	2	2	1	0	1	1
Flight-Related	1	0	0	0	0	0
Air-Ground	0	1	2	0	1	0
Class-A	1	1	0	0	0	0
Class-B	1	0	0	0	1	0
Class-C	1	2	3	0	1	1
Total	3	3	3	0	2	1

The variable Poisson process models that were fit to the original data were tested to determine if they adequately predicted the new data not used in the initial model. The modified denominator-free χ^2 test was used to determine the suitability of the estimates in this cross-validation. Table 13 shows model probabilities and the suitability of the models in predicting the new data. Since no estimation was involved, results were referenced to a χ_6^2 random. Cross-validation demonstrated that this model was suitable for predicting MRM probability distribution.

Table 13: Variable Poisson Process Model Cross-Validation

Mishap Classification	$P\left\{\chi_6^2 \geq \hat{\lambda}\right\}$	Suitability
Flight	.57	Not Unusual
Flight-Related	.93	Not Unusual
Aircraft-Ground	.30	Not Unusual
Class A	.80	Not Unusual
Class B	.82	Not Unusual
Class C	.23	Not Unusual
Total	.24	Not Unusual

D. PROBABILITIES AND EXPECTED FUTURE COSTS

Probability tables based on equations calculated by the variable Poisson process model were developed. The values obtained from the equations are means of hypothetical Poisson processes that produce the mishaps. These means were used to predict the likelihood of future mishaps. Probability tables for FY98 and the five-year period including FY98 through FY02 provide insight into a possible environment facing Naval Aviation in the near future. Table 14 presents a summary of the FY98 probability table found in Appendix E.

Table 14: FY98 Average Monthly MRM Probabilities

Mishap Classification	Number of Maintenance-Related Mishaps						
	0	1	2	3	4	5	6
Flight	.38	.37	.18	.06	.01	.00	.00
Flight-Related	.86	.13	.01	.00	.00	.00	.00
Aircraft-Ground	.19	.31	.26	.15	.06	.02	.01
Class A	.71	.24	.04	.01	.00	.00	.00
Class B	.64	.29	.06	.01	.00	.00	.00
Class C	.19	.31	.26	.15	.06	.02	.01
Total	.06	.17	.24	.22	.16	.09	.04

The hypothetical expected number of MRMs per year were calculated using the variable Poisson process model. Values are obtained by summing the hypothetical monthly means that were generated by the variable Poisson process model. Table 15 presents the expected number of mishaps for FY98 through FY02.

Table 15: Expected MRMs for FY98 - FY02

Mishap Classification	98	99	00	01	02
Flight	11.6	10.4	9.4	8.5	7.7
Flight-Related	1.8	1.5	1.3	1.1	0.9
Aircraft-Ground	20.2	18.1	16.2	14.6	13.0
Class-A	4.1	3.6	3.2	2.8	2.4
Class-B	5.3	5.0	4.8	4.5	4.3
Class-C	20.0	17.0	14.4	12.2	10.3
Total	33.5	30.0	26.8	24.0	21.5

Expected costs of MRMs for FY98 and for the five-year period including FY98 through F02 were calculated. Costs are assumed independent and identically distributed. Mishaps, N, are assumed Poisson and independent of cost. Cost is given by $Cost = \sum_{i=1}^{N} C_i$ and expected cost was calculated as follows:

$$E[Cost] = E[E[Cost \mid N]]$$
$$= E[N * E[C_i]]$$
$$= E[N] * E[C_i]$$

The variance of this expected cost is given by

$$Var[Cost] = Var[E[Cost \mid N]] + E[Var[Cost \mid N]]$$

$$= Var[N * E[C_i]] + E[N * Var[C_i]]$$

$$= E[C_i]^2 * Var[N] + E[N] * Var[C_i]$$

and the standard deviation is

$$SD = \sqrt{Var[Cost]}$$

Cost values were calculated using the expanded probability tables in Appendix F and the average costs of the MRMs for FY90 through FY97. The expected cost of Naval Aviation MRMs for FY98 and the five-year period from FY98 through FY02 are in Table 16. The total dollar value shown is an average of the cost totals for mishap Type, mishap Class, and mishap total. Cost calculated directly using the total mishap variable Poisson model was not used alone because cost is highly dependent on the Class and Type of the mishap.

Table 16: Expected Costs of Naval Aviation MRMs in FY98$M

Mishap Classification	FY98 Expected Cost	FY98 Standard Deviation	FY98-FY02 Expected Cost	FY98-FY02 Standard Deviation
Flight	95.54	13.72	394.04	87.86
Flight-Related	.21	0.26	0.77	21.34
Air-Ground	1.84	0.81	7.49	74.91
Class-A	55.26	35.59	216.99	55.97
Class-B	.19	1.15	9.84	40.41
Class-C	1.19	0.35	4.37	71.00
Total	72.62	12.55	294.41	96.29

E.   HUMAN ERROR IDENTIFICATION

The Naval Aviation MRMs are categorized according to the Human Factors Accident Classification System Maintenance Extension. The number of mishaps in which a second order human error causal factor is present was identified. These human error causal factors are categorized by the corresponding HFACS Maintenance Extension second order error types in Table 17.

Table 17: Frequency of Error Type by Accident Type and Class

	Unforeseen	Squadron	Environment	Equipment	Workspace	Medical	Personal Readiness	Crew-Resource Management	Error	Violation
FM	68	80	0	4	0	0	0	13	126	52
FRM	8	17	0	0	0	1	1	2	27	9
AGM	75	185	6	16	2	22	2	63	217	121
Class A	30	42	0	2	0	2	1	10	47	25
Class B	25	41	1	3	0	3	0	6	44	21
Class C	96	199	5	15	2	18	2	62	279	136
Total	151	282	6	20	2	23	3	78	370	182

Table 17 shows that over 95 percent of the human error casual factors identified can be attributed to five error types. These five error types in descending number are *error, squadron, violation, unforeseen,* and *crew-resource management.* These error types, with the exception of *unforeseen,* were examined further to determine the impact their reductions may have on MRMs.

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Figures 15 and 16 show the percentages of these error types in terms of a percentage of the total 470 mishaps analyzed.
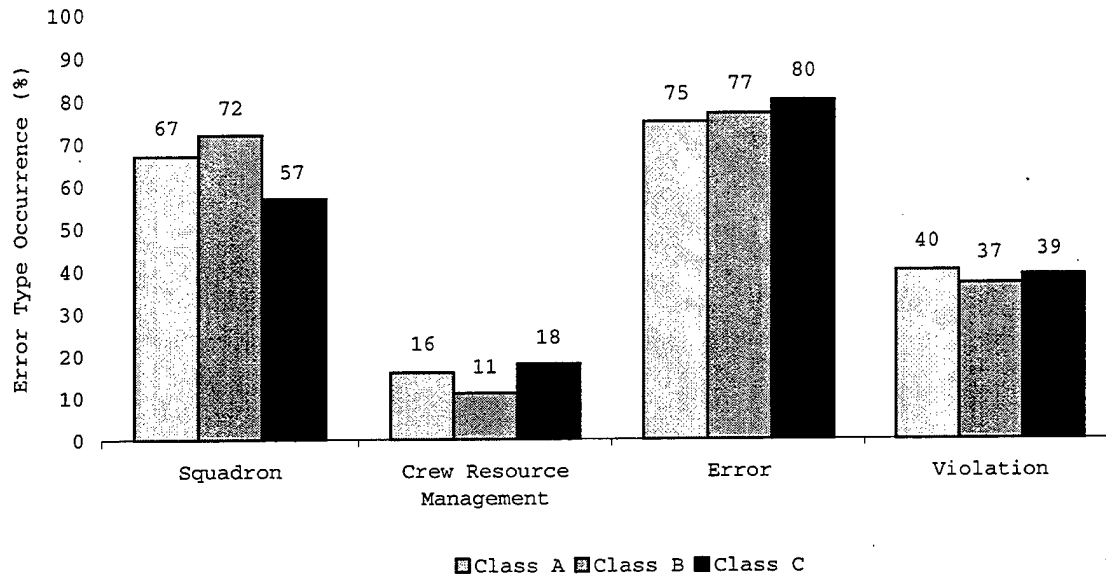
Figure 15: Percent of Human Error by Class
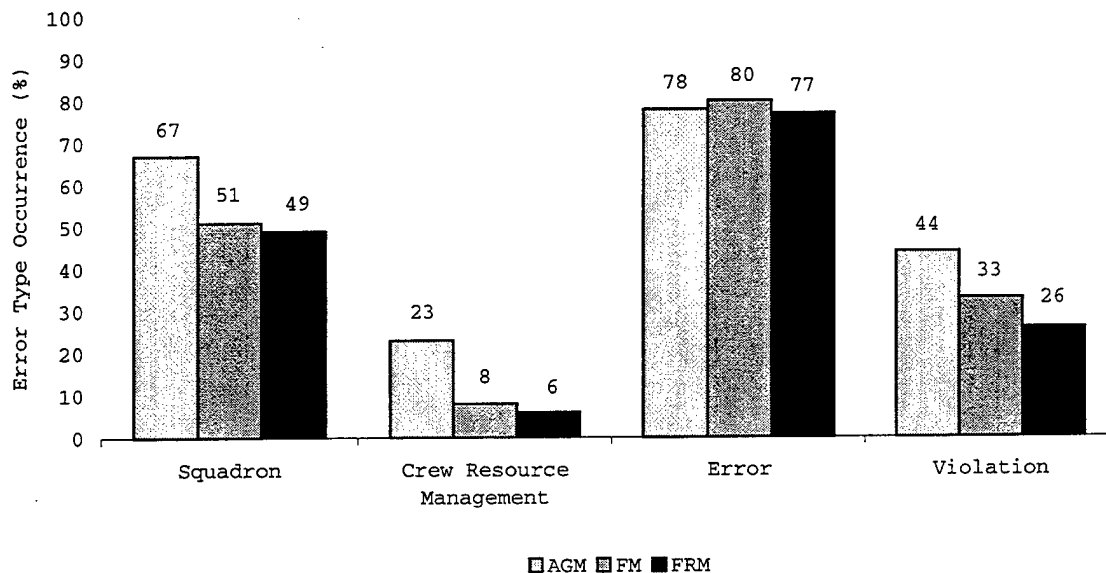
Figure 16: Percent of Human Error by Type

Figure 17 illustrates the rate of these five human error types per 100,000 flight-hours. The classifications of *squadron* and *error* have consistently been factors with the highest rates. However, rates of all four human error types per 100,000 flight-hours have dropped between 18 and 42 percent during the time-period studied.
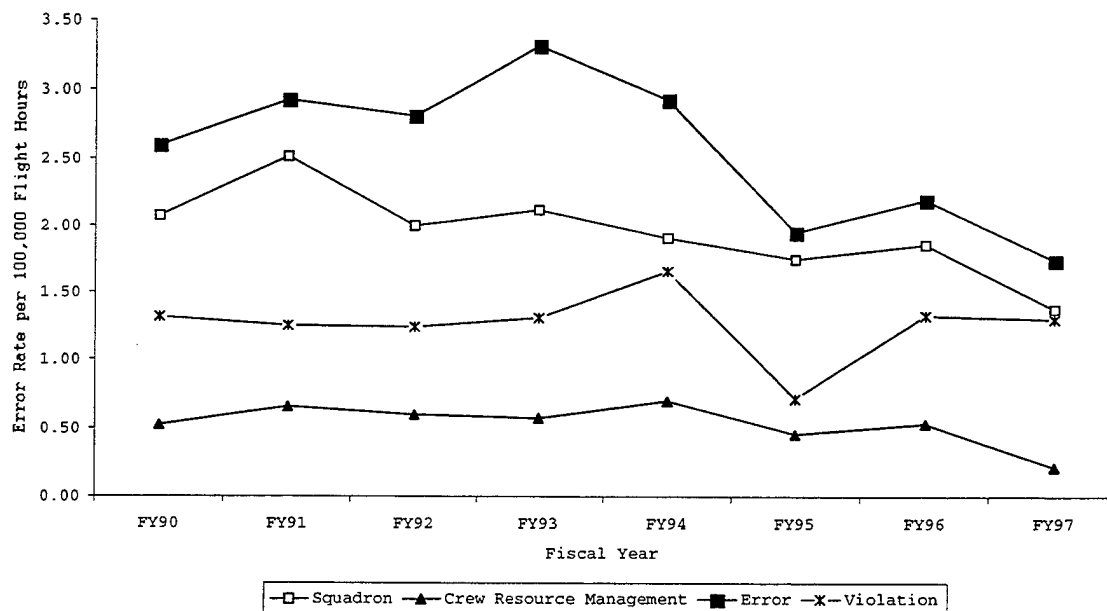
Figure 17: Error Rate per 100,000 Flight-Hours

F.   HUMAN ERROR IMPROVEMENT COST SAVINGS CALCULATIONS

Cost savings were based upon (a) the expected number of mishaps in the future, (b) the associated costs of those mishaps, and (c) the likelihood that human error played a role in the expected mishaps. Estimates based upon reductions of the occurrence of

human error by 10, 20, and 30 percent were estimated. Cost savings estimates were calculated as follows:

E[Cost savings] = E[N] * E[C_i] * %Error * %Reduction

Table 18 and Figure 18 show potential cost savings over both a one-year and five-year period.

Table 18: Potential Cost Savings (FY98$M)

Percent	Years	Supervisory	Crew Resource Management	Error	Violation
10	1	4.4	0.9	6.0	2.8
	5	18.1	3.5	24.8	11.3
20	1	8.8	1.7	12.1	5.5
	5	36.1	7.0	49.6	22.6
30	1	13.2	2.6	18.1	8.3
	5	54.2	10.5	74.3	33.9
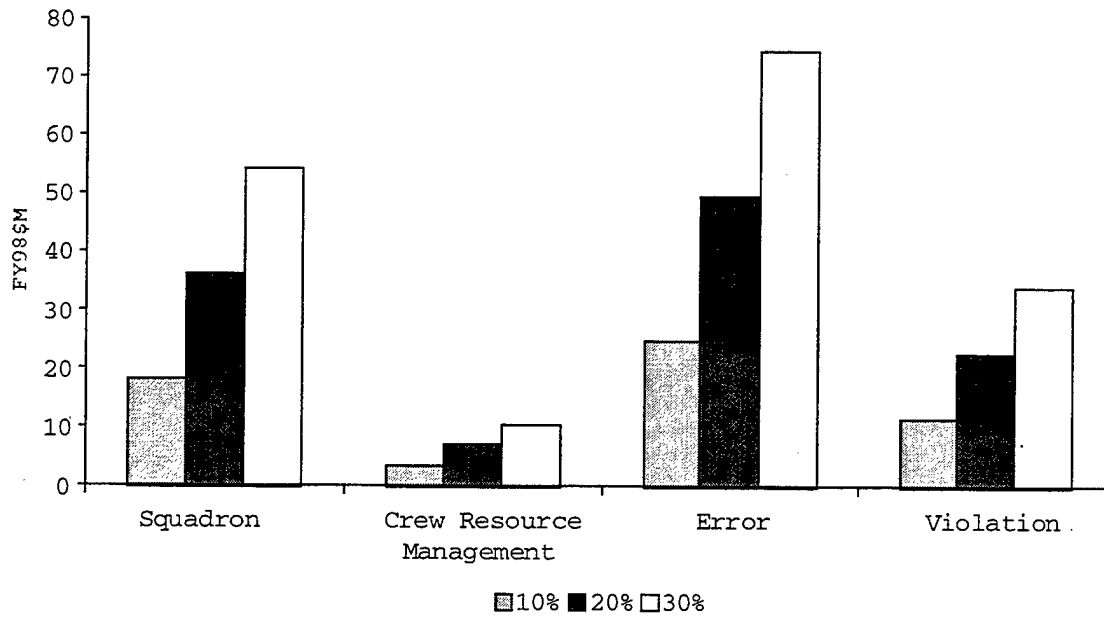
Figure 18: Five Year Cost-Savings FY98$M

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY

The effects of Naval Aviation mishaps are significant in terms of fatalities, costs, readiness, and mission capability. Throughout this past decade, Naval Aviation leadership has focused much attention on the role of aircrew error and this has contributed to an overall decrease in aviation mishaps. However, similar efforts have not been taken to address MRMs. During the 1990's, one in every four Naval Aviation mishaps were maintenance-related. Unless significant changes occur in the current operational environment, Naval Aviation will continue to rely on a diminishing number of fleet aircraft that are rapidly aging. The demands for aviation maintenance will continue to increase well into the 21st century, as will the opportunities for maintenance error.

Accident prevention programs are the primary means Naval Aviation has to reduce costs associated with aviation mishaps. Accidents historically were thought to be the result of single events, a belief that is still held by some. Only through an understanding of the systems that fail and the context in which these

failures occur can this belief be put to rest. This study shows that accidents are results of a complex combination of errors. Naval Aviation must address the issue of maintenance error. The only question that remains is where to target intervention strategies to reduce maintenance error. This study provides insights into maintenance error that, if acted upon, may mitigate the emerging maintenance problem.

The present research employed the Human Factors Accident Classification System (HFACS) maintenance extension. HFACS applies human error theories to aviation mishaps. The HFACS Maintenance Extension is an extension of the original HFACS taxonomy that includes human error associated directly with maintenance actions. The HFACS Maintenance Extension was used to classify 470 Naval Aviation MRMs according to specific human error types. Models were developed on the same mishap data to provide insight into the underlying processes that comprise Naval Aviation MRMs. The information obtained through this classification and modeling provided the basis to estimate the costs associated with human errors in Naval Aviation MRMs.

B. CONCLUSIONS

This study examined Naval Aviation mishaps in a systematic manner. The occurrence of maintenance error in past MRMs and mathematical models of mishaps were used to evaluate potential effects of maintenance error reduction programs. The HFACS Maintenance Extension was used to identify the most likely forms that maintenance error takes and the conditions associated with those errors. It then highlighted where to employ intervention strategies and gave the potential cost savings associated with that intervention.

The methodologies used in this study were well adapted to the mishaps examined. In particular, the variable Poisson process model provided the means to predict future mishaps and future costs. This particular model was chosen as the simplest model that was suitable for predicting future mishaps. The model predicts a *mean* number of MRMs based on a hypothetical Poisson process. Probability tables for the number of future mishaps were derived from the density function associated with the means of the hypothetical Poisson process model. This model was cross validated on six-months of additional data. The model was found to adequately statistically describe mishaps by Type, Class, and total number of

mishaps. The variable Poisson process model used in conjunction with the HFACS Maintenance Extension allowed for the prediction of cost saving estimates for human error reduction strategies.

The average number of mishaps predicted by this model per year over the next five years ranged from 22 to 33 per year. Based on these values, the expected cost of MRMs for FY98 was nearly 60 million dollars and well over 200 million for FY98 through FY02.

The HFACS Maintenance Extension categories of *error*, *squadron*, *violation*, *unforeseen*, and *crew-resource management* were the most significant contributors to cost. At least one of these five error dimensions occurred in over 95 percent of the 470 mishaps studied. An analysis of potential reductions in these error types revealed that reductions as low as 10 percent for a single error type can produce cost savings of over one million dollars annually.

C.   RECOMMENDATIONS

The use of the HFACS Maintenance Extension is recommended to make the study of MRMs more rigorous. Using the Maintenance Extension, particularly its taxonomy, allows human error intervention strategies to

be identified and prioritized. This taxonomy is appropriate for the study of aviation maintenance mishaps, as well as other accidents that have associated maintenance error as causal factors.

It is recommended that the Naval Safety Center and the Naval Air Systems Command work toward revising the current procedures for aviation accident investigation and mishap reporting to include the HFACS Maintenance Extension. Adding the extension would increase the usefulness of the existing aviation mishap database by standardizing the reporting of MRMs and would aid investigators in assessing factors associated with mishaps.

Further, it is recommended that the Naval Safety Center and Naval Air Systems Command lead an effort to study trends in Naval Aviation mishaps using simple mathematical models as well as more advanced techniques not employed here. Human error theory suggests that the complex interactions of several factors result in accidents. This suggests that multivariate mathematical techniques that directly consider factors such as flight-hours flown, number of fleet aircraft, and average age of aircraft, would be appropriate.

Valid models of accident causation must predict future accident scenarios. Additional research evaluating other possible models is recommended. The analysis of different mathematical models for the prediction of Naval Aviation mishaps and mishap costs may identify models that are more suitable than those used in this research.

APPENDIX A: MONTHLY NUMBER OF MAINTENANCE-RELATED MISHAPS BY TYPE AND CLASS FOR FY90-FY98

Table A1: Flight Mishaps by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	1	0	2	4	0	2	1	2	12
November	2	4	1	1	2	1	1	0	12
December	2	1	0	1	2	1	1	1	9
January	4	6	1	1	2	1	2	2	19
February	3	2	1	1	1	0	2	0	10
March	1	1	4	2	2	3	2	1	16
April	2	1	2	1	0	0	0	1	7
May	1	2	2	3	2	2	1	2	15
June	1	2	4	3	2	0	1	1	14
July	1	4	1	1	3	0	1	2	13
August	2	6	0	1	2	1	1	1	14
September	1	1	2	2	1	0	2	0	9
Total	21	30	20	21	19	11	15	13	150

Table A2: Flight-Related Mishaps by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	2	0	0	1	1	0	0	0	4
November	0	2	1	0	0	0	0	0	3
December	0	1	0	1	0	0	0	0	2
January	0	2	0	0	0	0	1	1	4
February	0	0	0	0	0	1	1	0	2
March	2	0	1	0	2	0	0	0	5
April	0	0	0	0	1	0	0	0	1
May	1	0	1	2	0	0	0	0	4
June	0	1	1	0	0	0	1	0	3
July	0	0	1	0	0	0	0	0	1
August	0	0	0	0	0	0	0	0	0
September	0	1	1	1	1	0	1	0	5
Total	5	7	6	5	5	1	4	1	34

Table A3: Aircraft-Ground Mishaps by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	4	2	4	3	2	4	4	4	27
November	4	2	3	0	3	1	1	0	14
December	1	4	2	3	1	4	0	2	17
January	3	5	6	4	4	3	5	0	30
February	5	3	1	5	4	0	3	3	24
March	5	3	5	3	3	4	2	1	26
April	2	3	3	1	2	2	1	2	16
May	4	3	5	1	2	2	3	3	23
June	3	2	2	6	6	2	0	1	22
July	4	6	4	8	5	2	2	1	32
August	3	6	1	4	2	1	1	1	19
September	4	7	3	4	1	2	1	1	23
Total	42	46	39	42	35	27	23	19	273

Table A4: Class A Mishaps by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	1	0	1	1	0	1	1	2	7
November	1	1	0	1	1	1	0	0	5
December	1	2	0	0	0	0	0	0	3
January	3	2	2	0	0	1	0	0	8
February	0	0	0	0	0	0	1	0	1
March	0	0	2	2	0	1	1	0	6
April	2	0	1	0	0	0	0	0	3
May	1	1	0	1	1	0	1	1	6
June	1	0	1	2	1	0	0	0	5
July	0	1	2	3	0	0	0	0	6
August	1	2	0	0	1	1	0	1	6
September	0	0	1	1	1	0	1	1	5
Total	11	9	10	11	5	5	5	5	61

Table A5: Class B Mishaps by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	1	0	1	1	0	1	1	0	5
November	3	1	1	0	0	0	0	0	5
December	0	0	0	0	0	2	0	2	4
January	0	0	1	0	0	1	2	0	4
February	0	2	0	0	0	1	0	0	3
March	0	0	0	0	1	2	0	1	4
April	0	2	1	2	0	1	1	1	8
May	0	2	1	0	0	0	1	1	5
June	0	1	0	1	1	0	0	0	3
July	1	0	0	0	2	0	0	0	3
August	0	3	0	2	0	0	0	0	5
September	1	2	1	0	0	0	2	0	6
Total	6	13	6	6	4	8	7	5	55

Table A6: Class C Mishaps by FY

Time Period	90	91	92	93	94	95	96	97	Total
October	5	2	4	6	3	4	3	4	31
November	2	6	4	0	4	1	2	0	19
December	2	4	2	5	3	3	1	1	21
January	4	11	4	5	6	2	6	3	41
February	8	3	2	6	5	0	5	3	32
March	8	4	8	3	6	4	3	1	37
April	2	2	3	0	3	1	0	2	13
May	5	2	7	5	3	4	2	3	31
June	3	4	6	6	6	2	2	2	31
July	4	9	4	6	6	2	3	3	37
August	4	7	1	3	3	1	2	1	22
September	4	7	4	6	2	2	1	0	26
Total	51	61	49	51	50	26	30	23	341

APPENDIX B: ALTERNATIVE MODELS FOR THE PREDICITION OF HYPOTHETICAL MEANS OF POISSON RANDOM VARIABLES

The Homogeneous Poisson Process Model

The homogeneous Poisson process model is a relatively simple mathematical model. This model attempts to fit a single parameter to a set of data. The underlying arrival process that produced the data is considered Poisson with mean λy. λy is assumed to be the mean value of a Poisson distribution of random variables. The MRM data was examined by year, by twelve-month period, and by month. Figures B1 and B2 show the number of MRMs by fiscal year.
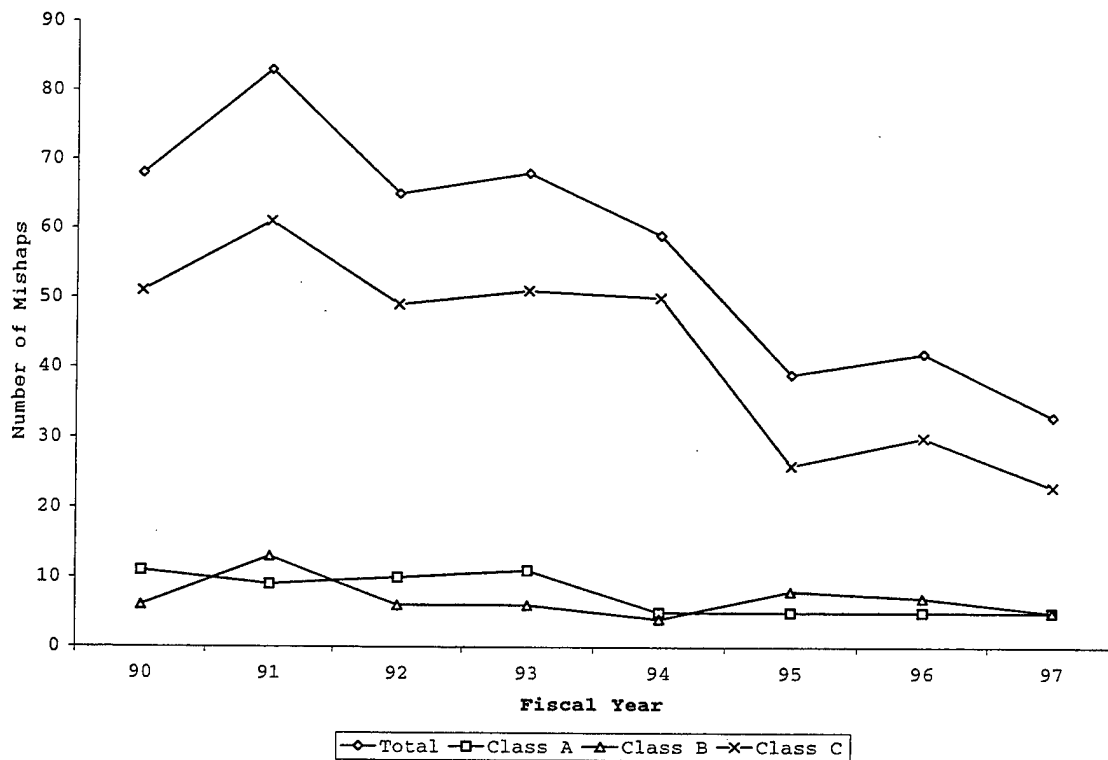
Figure B1: Maintenance-Related Mishap Class by FY
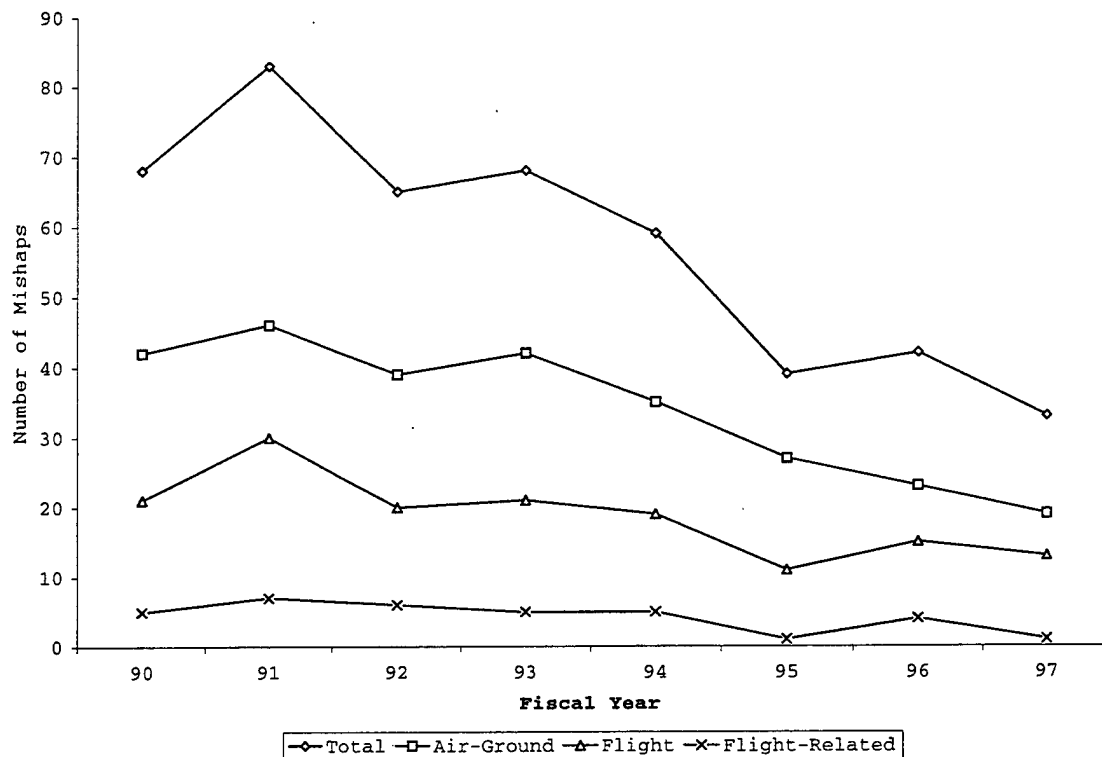
Figure B2: Maintenance-Related Mishap Type by FY

The estimate of λ_y is $\hat{\lambda}_y = \dfrac{\sum_{i=1990}^{1997} y_i}{n}$. A $\hat{\lambda}_y$ was calculated for all Classes and Types of mishap as well for the total number of mishaps. The classical χ^2 test was used to determine the suitability of this estimate. The goodness of fit test compared $\sum_{i=1990}^{1997} \dfrac{(y_i - \hat{\lambda}_y)^2}{\hat{\lambda}_y}$ to a χ_7^2 distribution obtaining a probability, $P\{\chi_7^2 \geq \hat{\lambda}_y\}$.

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Table B1: FY Homogenous Poisson Process Model

Mishap Classification	$\hat{\lambda}_y$	$P\left\{\chi_7^2 \geq \hat{\lambda}_y\right\}$	Suitability
Flight	18.8	0.005	Unlikely
Flight-Related	4.6	0.070	Not unusual
Air-Ground	34.1	0.343	Not unusual
Class A	7.6	0.370	Not unusual
Class B	6.9	0.361	Not unusual
Class C	42.6	<0.001	Unlikely
Total	57.1	<0.001	Unlikely

The homogeneous Poisson process model adequately statistically describes the yearly data for FRMs, AGMs, Class A mishaps, and Class B mishaps. However, the homogenous Poisson process model is not appropriate for modeling the yearly total number of MRMs or Class C mishaps.

Figures B3 and B4 show the number of MRMs by twelve-month period.
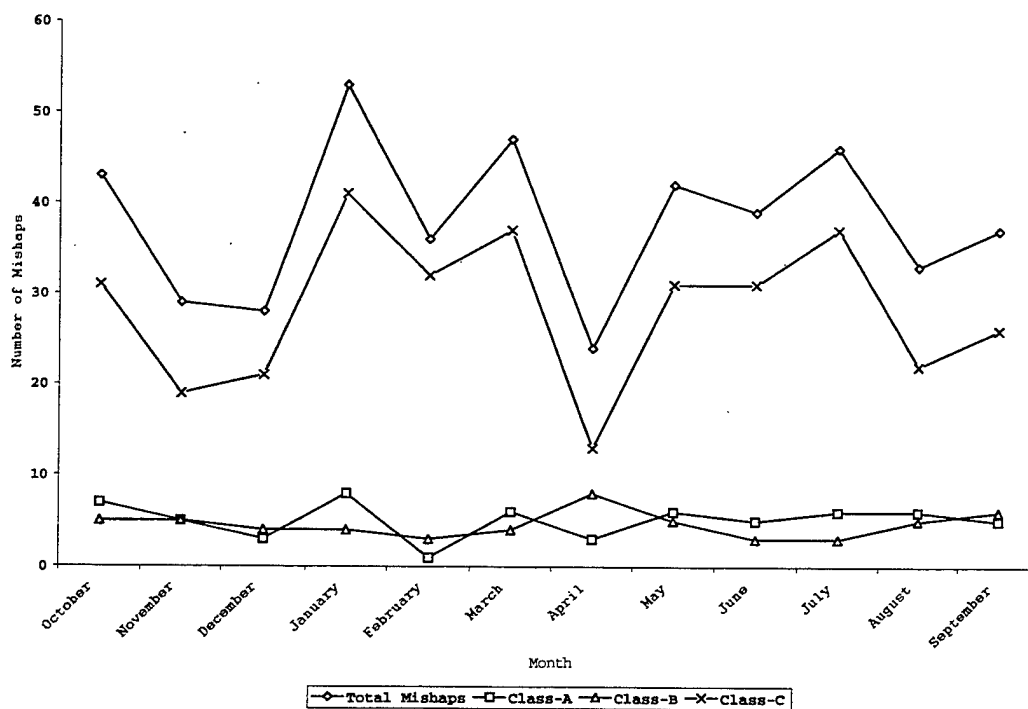
Figure B3: Twelve-Month Mishap Class by Month
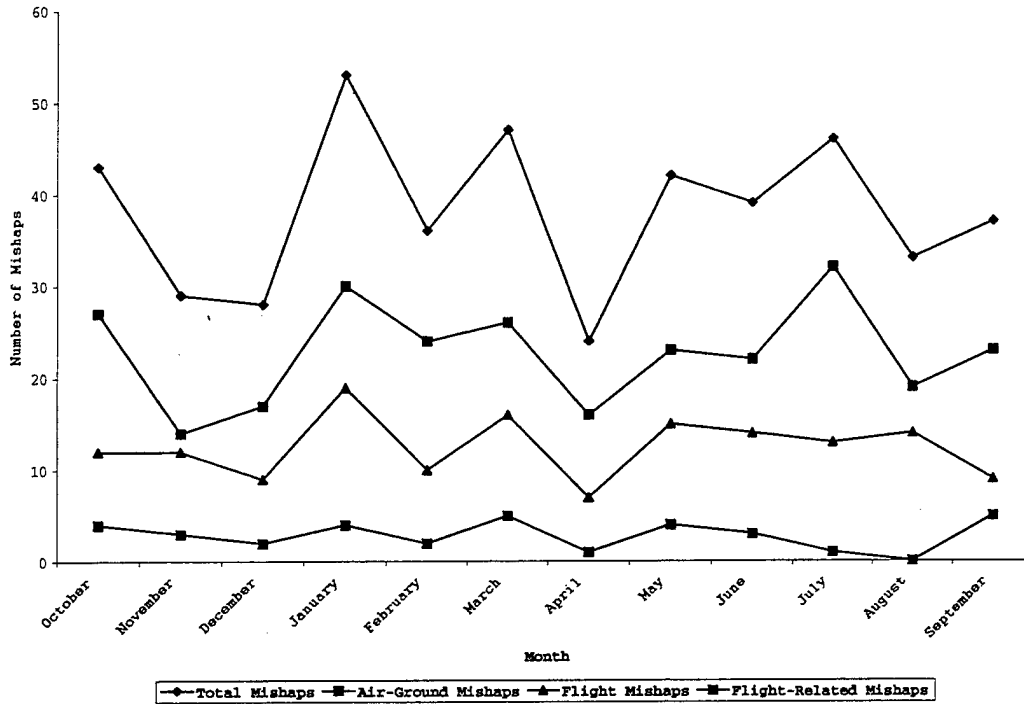
Figure B4: Twelve-Month Mishap Type by Month

The estimate of λ_m is $\hat{\lambda}_m = \dfrac{\sum_{i=October}^{September} m_i}{12}$. A $\hat{\lambda}_y$ was calculated for all Classes and Types of mishap as well for the total number of mishaps. The classical χ^2 test was used to determine the suitability of this estimate. The goodness of fit test compared $\sum_{i=October}^{September} \dfrac{(m_i - \hat{\lambda}_m)^2}{\hat{\lambda}_m}$ to a χ_{11}^2 distribution obtaining a probability, $P\{\chi_{11}^2 \geq \hat{\lambda}_m\}$.

Table B2: Twelve-Month Homogenous Poisson Process Model

Mishap Classification	$\hat{\lambda}_y$	$P\{\chi_7^2 \geq \hat{\lambda}_y\}$	Suitability
Flight	12.5	0.516	Not unusual
Flight-Related	2.8	0.489	Not unusual
Air-Ground	22.8	0.189	Not unusual
Class-A	5.1	0.709	Not unusual
Class-B	4.6	0.931	Not unusual
Class-C	28.4	0.005	Unlikely
Total	38.1	0.029	Unlikely

The homogeneous Poisson process model adequately statistically describes the twelve-month data for FMs, FRMs, AGMs, Class A mishaps, and Class B mishaps. The twelve-month total number of MRMs and Class C mishaps for each month may not be adequately described by a homogeneous Poisson random variable.

The estimate of λ_a is $\hat{\lambda}_a = \dfrac{\sum_{i=October1989}^{September1997} a_i}{96}$. A $\hat{\lambda}_a$ was calculated for all Classes and Types of mishap as well for the total number of mishaps. The modified denominator-free χ^2 test was used for mishap data separated by type and class. This goodness of fit test compared $\sum_{i=October1989}^{September1997}\left(\sqrt{a_i} + \sqrt{a_i+1} - \sqrt{4*\hat{\lambda}_a+1}\right)^2$ to a χ^2_{95} distribution obtaining a probability, $P\{\chi^2_{95} \geq \hat{\lambda}_a\}$.

Table B3: Continuous-Month Homogenous Poisson Process Model

Mishap Classification	$\hat{\lambda}_a$	$P\{\chi^2_{95} \geq \hat{\lambda}_a\}$	Suitability
Flight	1.6	0.855	Likely
Flight-Related	0.4	0.999	Likely
Air-Ground	2.8	0.221	Likely
Class-A	0.6	0.970	Likely
Class-B	0.6	0.931	Likely
Class-C	3.6	0.003	Unlikely
Total	4.8	0.005	Unlikely

The homogeneous Poisson process model adequately statistically describes the continuous-month data for FM, FRM, AGM, Class A, and Class B mishaps. However, the homogeneous Poisson process model is not appropriate for modeling the continuous-month total number of MRMs or Class C mishaps.

The Non-Homogeneous Poisson Process Model

The total number of MRMs and Class C mishaps were not adequately described by any of the three homogeneous Poisson process models proposed. Although the model was unlikely, the continuous-month homogeneous Poisson process model had the highest likelihood of being an adequate estimator. Based on this, and trends noted in the data, a continuous month non-homogenous piece-wise constant rate function was examined.

The variance of Poisson random variables equals its mean. Therefore in data, of which there is a significant range in the size of counts per time unit, problems may arise because the larger the count the greater the variability. An examination of the square root of the count data can be beneficial in decreasing the effects of this problem. Figure B5 shows the square root of the monthly counts.
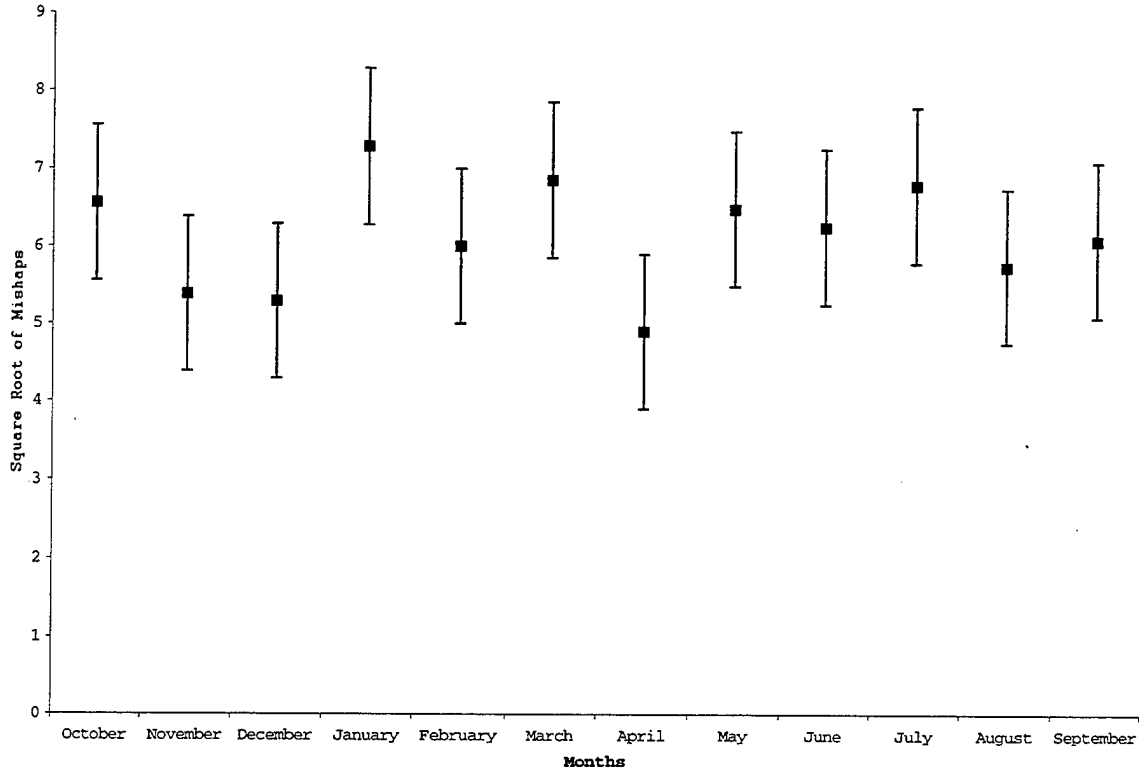
Figure B5: Square Roots of Mishaps by Month

An examination of Figure B5 confirms that a non-homogeneous Poisson process may be appropriate. In order to fit a non-homogenous Poisson process with a piecewise constant rate function, months were partitioned into two groups. The proposed model, $\lambda_i = \lambda_L$ for the six months with the lowest average number of mishaps (November, December, February, April, August, and September) and $\lambda_i = \lambda_H$ the other months, was then tested.

The means λ_L and λ_H were estimated to determine whether the distribution of the total number of MRMs for each month can be described by a non-homogeneous Poisson process. The estimate of λ_L is $\hat{\lambda}_L = \dfrac{29+28+36+24+33+37}{6} = 31.17$ and the estimate of λ_H is

$\hat{\lambda}_H = \dfrac{43+53+47+42+39+46}{6} = 45$. The classical χ^2 goodness of fit test resulted in $\sum_{i=1}^{6(LowMonths)} \dfrac{(m_i - \hat{\lambda}_l)^2}{\hat{\lambda}_l} + \sum_{i=1}^{6(HighMonths)} \dfrac{(m_i - \hat{\lambda}_h)^2}{\hat{\lambda}_h} = $ 6.69. This value compared to a χ^2_{10} distribution, $P\{\chi^2_{10} \geq 6.69\}$, obtains a probability of 0.754. Therefore, the values of 31.17 and 45 for λ_L and λ_H, respectively are not that unusual.

The means λ_L and λ_H were estimated to determine whether the distribution of Class C mishaps for each month can be described by a non-homogeneous Poisson process. The estimate of λ_L is $\hat{\lambda}_L = \dfrac{19+21+32+13+22+26}{6} = 22.17$ and the estimate of λ_H is $\hat{\lambda}_H = \dfrac{31+41+37+31+31+37}{6} = 34.67$. The classical χ^2 goodness of fit test resulted in $\sum_{i=1}^{6(LowMonths)} \dfrac{(m_i - \hat{\lambda}_l)^2}{\hat{\lambda}_l} + \sum_{i=1}^{6(HighMonths)} \dfrac{(m_i - \hat{\lambda}_h)^2}{\hat{\lambda}_h} = $ 11.97. This value compared to a χ^2_{10} distribution, $P\{\chi^2_{10} \geq 11.97\}$, obtains a probability of 0.287. Therefore, the values of 22.17 and 34.47 for λ_L and λ_H, respectively are not that unusual. The non-homogenous Poisson process model adequately statistically describes the total number of MRMs and Class C mishaps.

Cross-validation of Homogeneous and Nonhomogeneous Poisson Process Models

Mishap data for October 1997 through March of 1998 were obtained and used to cross-validate the models based on the fiscal year 1990 through 1997 data. The

homogeneous and nonhomogeneous Poisson process fitted models which best fit the original data. This was suggested by their associated probability values; they were tested to determine if they adequately described the new data. The two models tested were the:

- nonhomogenous Poisson process model for the total number of mishaps and Class C mishaps with rates $\hat{\lambda}_L$ and $\hat{\lambda}_H$.

- and the continual-month homogeneous Poisson process models for FMs, FRMs, and AGMs, Class A mishaps, and Class B mishaps with rate $\hat{\lambda}_a$.

The classical χ^2 test was used for the total number of mishaps and Class C data and the denominator-free goodness of fit test was used for the other data. Since no estimation was involved, both results were referenced to a χ_6^2 random variable.

Table B4. Cross-Validation of Homogeneous and Nonhomogeneous Poisson Process Models

Mishap Classification	$P\{\chi_6^2 \geq \hat{\lambda}\}$	Suitability
Flight	0.744	Not unusual
Flight-Related	0.895	Not unusual
Aircraft-Ground	0.001	Unlikely
Class A	0.720	Not unusual
Class B	0.760	Not unusual
Class C	0.006	Unlikely
Total	<0.001	Unlikely

Homogeneous Poisson process models adequately statistically describe FMs, FRMs, Class A mishaps, and Class B mishaps. However, a homogeneous Poisson process

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model may not be appropriate for modeling AGMs and the non-homogeneous Poisson process model may not be appropriate for the total number of MRMs and Class C mishaps.

Moving Average Method

The moving average estimation technique is a method to generate an estimator based on the average of historical data. In this technique it is assumed that the overall number of mishaps on month i is a realization of a Poisson random variable with mean λ_i. The expected value λ_{i+1} in month span+1 is predicted by the average of a preceding span of months' values, $\hat{\lambda}_{Span+1} = \dfrac{\sum_{i=1}^{Span} m_i}{Span}$. The mean squared error over all the predictions from month span+1, up to and including the last month of analysis is calculated. This is completed for every value of span from one up to the maximum span of eighty-four. For each span an associated average sum of squared error is calculated. The span with the smallest average sum of squared error is then chosen as the estimator for this mathematical model.

The first step in the moving average method is to determine the optimal span which produced the minimum average squared error. An SPLUS program was written and executed which produced the average squared error for span lengths ranging from two through eighty-four. The

Span length that on average produced a minimal amount of mean squared error and was used as a basis to calculate estimators. The spans that had the minimal amount of mean squared error for FM, FRM, AGM, Class A, Class B, and Class C mishaps were 38, 44, 46, 46, 24, and 38 respectively.

The estimate of λ_m is $\hat{\lambda}_m = \dfrac{\sum_{i=1}^{Span} m_i}{Span}$. The modified denominator-free χ^2 test was used to evaluate the model. This goodness of fit test compared $\sum_{i=1}^{96-Span}\left(\sqrt{m_i} + \sqrt{m_i+1} - \sqrt{4*\hat{\lambda}_m+1}\right)^2$ to a $\chi^2_{96-Span}$ distribution obtaining a probability, $P\left\{\chi^2_{96-Span} \geq \hat{\lambda}_m\right\}$.

Table B5: Moving average Model

Mishap Classification	Span	$P\left\{\chi^2_{96-Span} \geq \hat{\lambda}_m\right\}$	Suitability
Flight	38	0.946	Not unusual
Flight-Related	44	0.999	Not unusual
Air-Ground	46	0.179	Not unusual
Class A	46	0.974	Not unusual
Class B	24	0.937	Not unusual
Class C	38	0.059	Not unusual
Total	38	0.204	Not unusual

The moving average model adequately statistically describes the monthly data for total MRMs, FMs, FRMs, AGMs, Class A mishaps, Class B mishaps, and Class C mishaps.

Cross-validation of the moving average model

The moving average models that were fit to the original data were tested to determine if they adequately described the six-months of new data. The

denominator-free goodness of fit test was used for all data. Since no estimation was involved, both results were referenced to a χ_6^2 random variable.

Table B6: Cross-validation of the moving average model

Mishap Classification	$P\{\chi_6^2 \geq \hat{\lambda}\}$	Suitability
Flight	0.946	Not unusual
Flight-Related	0.999	Not unusual
Air-Ground	0.042	Unlikely
Class A	0.803	Not unusual
Class B	0.790	Not unusual
Class C	0.413	Not unusual
Total	0.198	Not unusual

The moving average model adequately statistically describes the total number of mishaps, FMs, FRMs, AGMs, Class A, Class B, and Class C mishaps.

APPENDIX C: VARIABLE POISSON PROCESS COMPUTER PROGRAM

MAIN

```
function(data, a.start = 15, b.start = 1, scale = 1/100){
#
# Main function to fit the Poisson/exponential model.
#
# Arguments: data, the set of putative Poisson counts
#            a.start, b.start: starting values
#            scale: Scale factor for numerics
# Return value: output from nlmin
#
# Step one: put data and scale into frame 1 for FUNC
#
    assign("data", data, frame = 1)
    assign("scale", scale, frame = 1)   #
#
# Call nlmin
#
    out <- nlmin(d.func, c(a.start, b.start),
    max.iter = 100)#
    plot(data, main = paste("Poisson Model for",
        substitute(data)), xlab = "Month", ylab
         = "Mishaps", type = "b")
    y.seq <- out$x[1] * exp( - out$x[2] * (1:length(
        data)) * scale)
    lines(1:length(data), y.seq, col = 8)
    return(out)
}
```

FUNC

```
function(param){
#
# FUNC: function for doing ML estimation in the
# Poisson/exponential model.
#
# Arguments: param, vector of parameters
# (The data is "data" in frame 1.)
#
# 1: get parameters and data
    a <- param[1]
    b <- param[2]
    data <- get("data", frame = 1)
    scale <- get("scale", frame = 1)    #
# 2: Set up the "t" vector with multipler of "scale".
#
    tt <- (1:length(data)) * scale#
#
# Compute the two terms in the likelihood; square, add them.
#
    first <- sum(data/a - exp( - b * tt))
    second <- sum(tt * (a * exp( - b * tt) - data))
    return(first^2 + second^2)
}
```

APPENDIX D: FITTED VARIABLE POISSON PROCESS MODELS FOR MISHAP TYPE AND CLASS
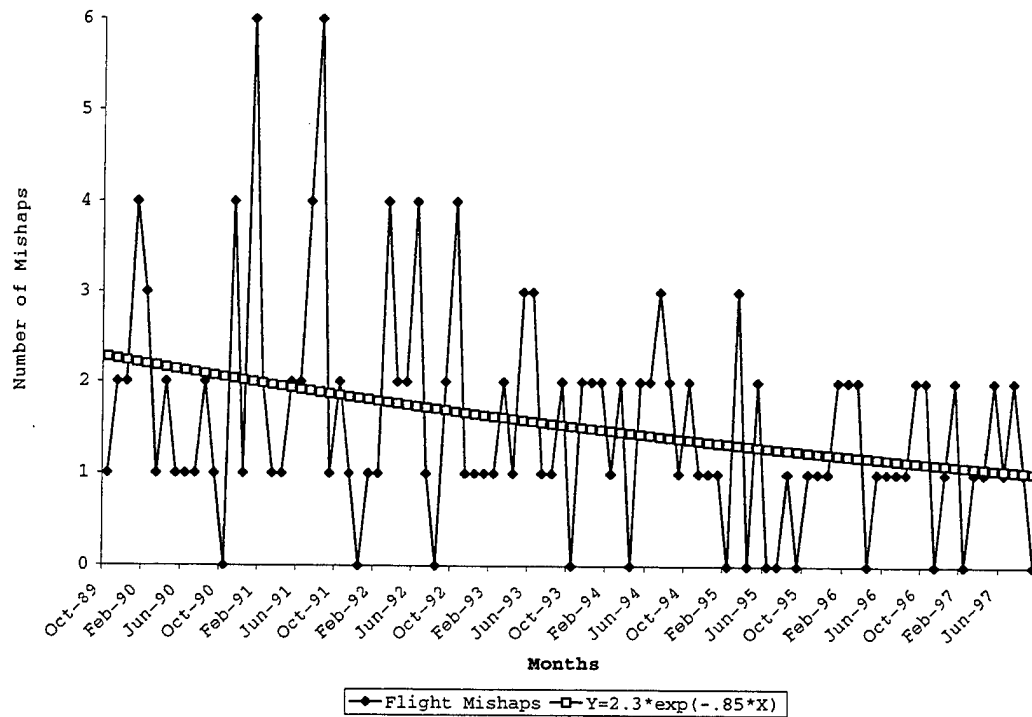
Figure D1: Variable Poisson Process for MRM FMs
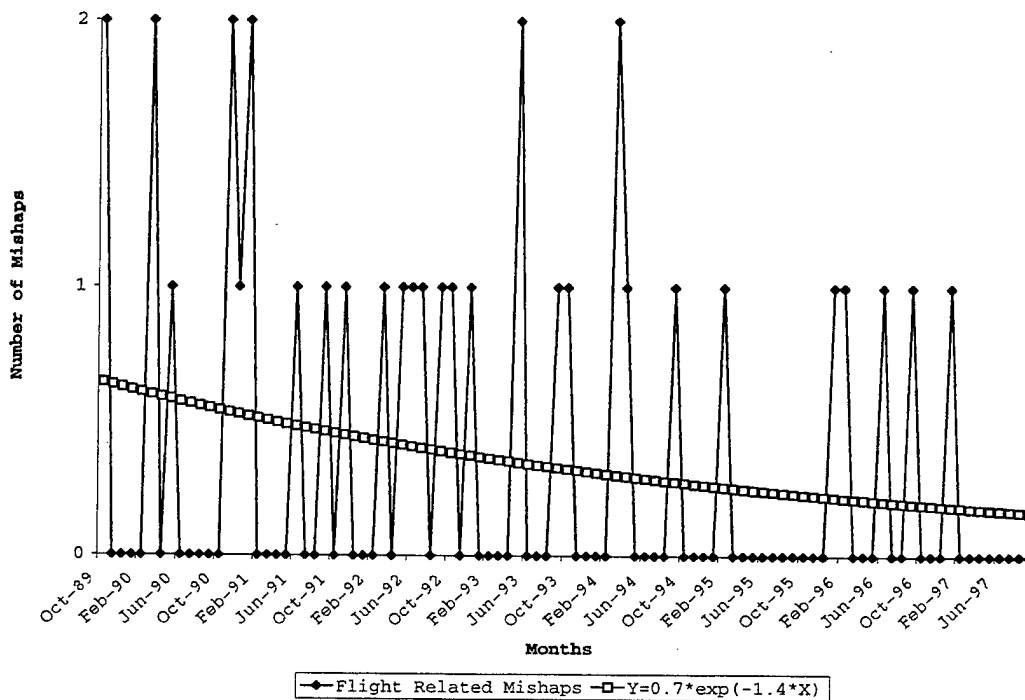
Figure D2: Variable Poisson Process for MRM FRMs

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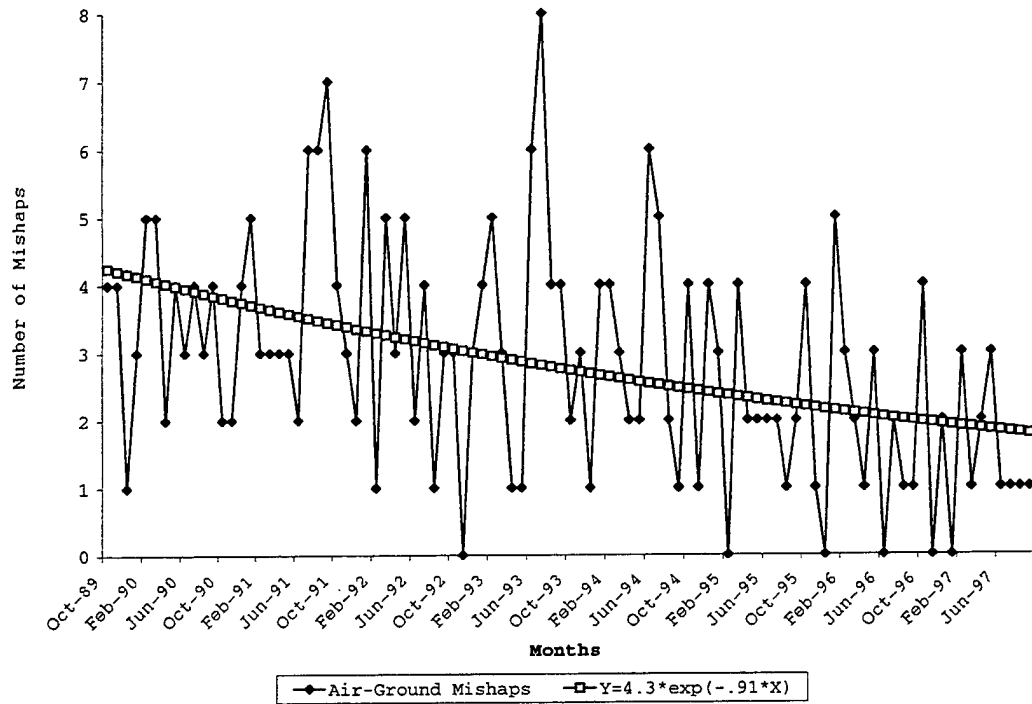
Figure D3: Variable Poisson Process for MRM AGM
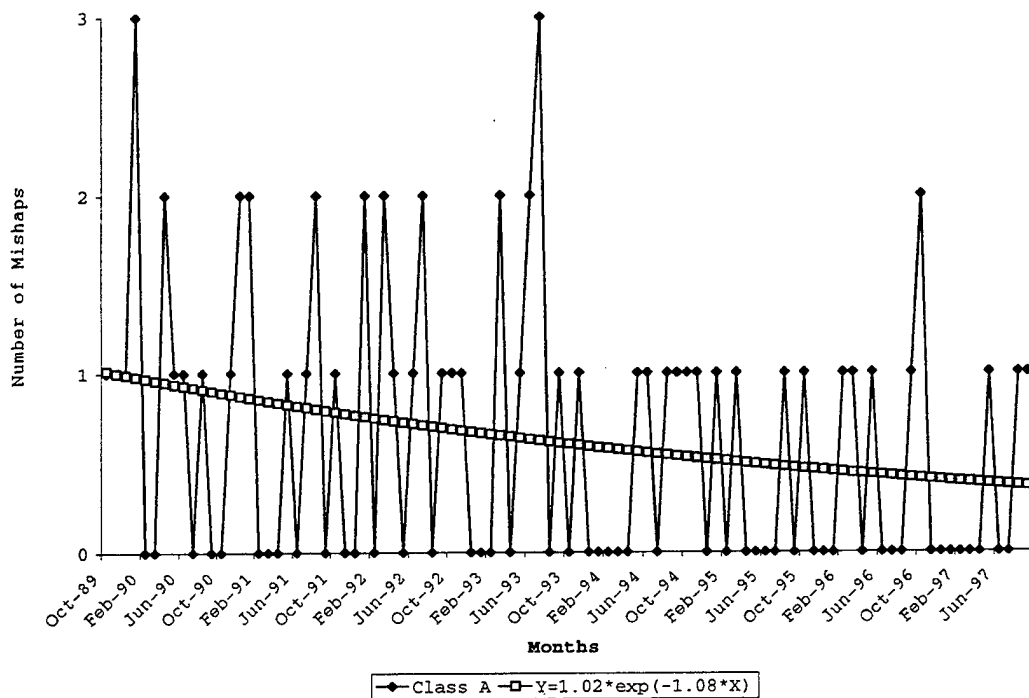
Figure D4: Variable Poisson Process for Class A MRMs

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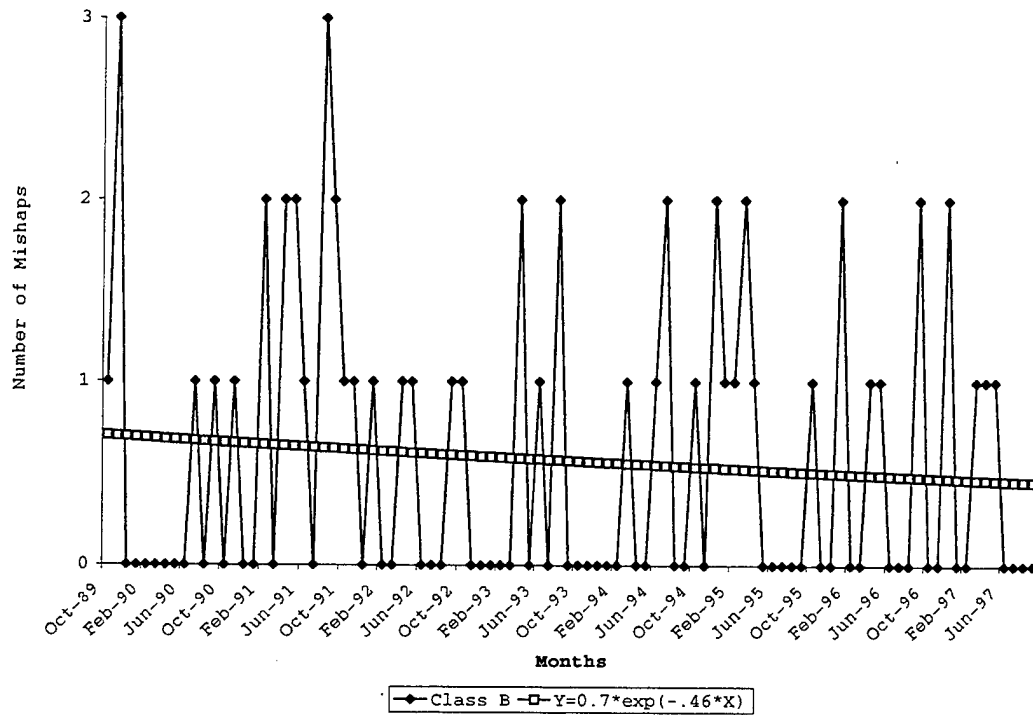
Figure D5: Variable Poisson Process for Class B MRMs
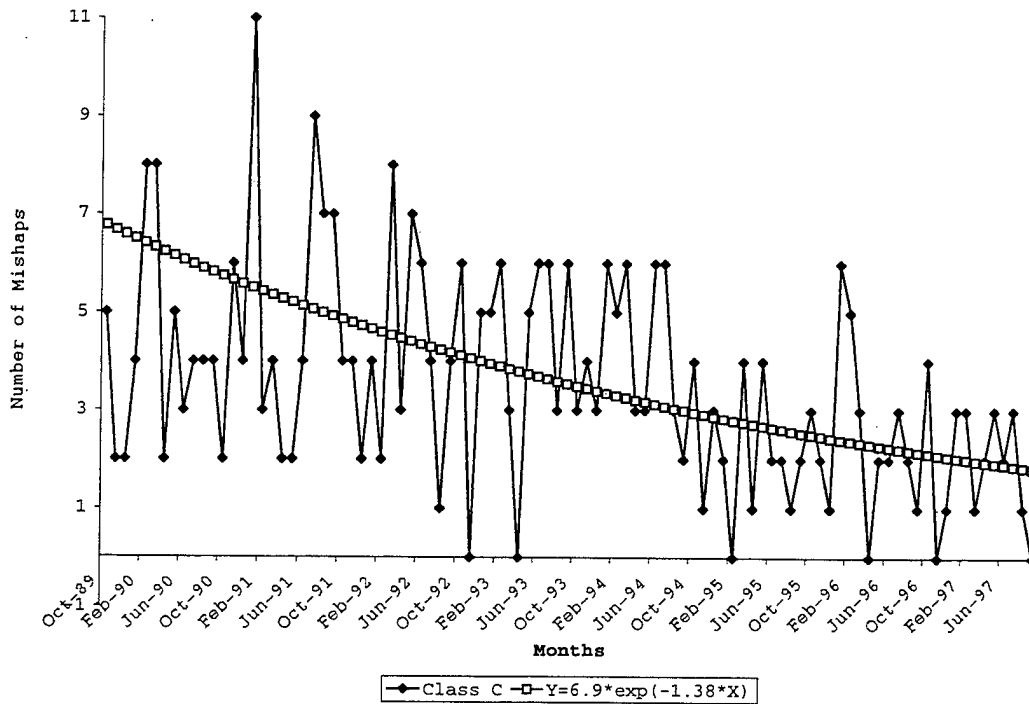
Figure D6: Variable Poisson Process for Class C MRMs

APPENDIX E: PROBABILITY TABLES FOR THE OCCURRENCE OF MAINTENANCE-RELATED MISHAPS

Table E1: FY98 Flight Mishap Probability Table

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
Oct97	1.01	0.36	0.37	0.19	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Nov97	1.00	0.37	0.37	0.18	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Dec97	0.99	0.37	0.37	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Jan98	0.98	0.37	0.37	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Feb98	0.98	0.38	0.37	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Mar98	0.97	0.38	0.37	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Apr98	0.96	0.38	0.37	0.18	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
May98	0.95	0.39	0.37	0.17	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Jun98	0.94	0.39	0.37	0.17	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Jul98	0.94	0.39	0.37	0.17	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Aug98	0.93	0.40	0.37	0.17	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Sep98	0.92	0.40	0.37	0.17	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00

Table E2: FY98 Flight-Related Mishap Probability Table

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
Oct97	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov97	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec97	0.16	0.85	0.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jan98	0.16	0.85	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb98	0.16	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar98	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr98	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May98	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jun98	0.15	0.86	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul98	0.14	0.87	0.13	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug98	0.14	0.87	0.12	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep98	0.14	0.87	0.12	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table E3: FY98 Aircraft-Ground Mishap Probability Table

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
Oct97	1.77	0.17	0.30	0.27	0.16	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Nov97	1.75	0.17	0.30	0.27	0.16	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Dec97	1.74	0.18	0.31	0.27	0.15	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Jan98	1.72	0.18	0.31	0.26	0.15	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Feb98	1.71	0.18	0.31	0.26	0.15	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Mar98	1.69	0.18	0.31	0.26	0.15	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Apr98	1.68	0.19	0.31	0.26	0.15	0.06	0.02	0.01	0.00	0.00	0.00	0.00
May98	1.66	0.19	0.32	0.26	0.15	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Jun98	1.65	0.19	0.32	0.26	0.14	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Jul98	1.63	0.20	0.32	0.26	0.14	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Aug98	1.62	0.20	0.32	0.26	0.14	0.06	0.02	0.00	0.00	0.00	0.00	0.00
Sep98	1.60	0.20	0.32	0.26	0.14	0.06	0.02	0.00	0.00	0.00	0.00	0.00

Table E4: FY98 Class A Mishap Probability Table

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
Oct97	0.36	0.70	0.25	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov97	0.36	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec97	0.35	0.70	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jan98	0.35	0.71	0.25	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb98	0.35	0.71	0.24	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar98	0.34	0.71	0.24	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr98	0.34	0.71	0.24	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May98	0.33	0.72	0.24	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jun98	0.33	0.72	0.24	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul98	0.33	0.72	0.24	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug98	0.32	0.72	0.23	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep98	0.32	0.73	0.23	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table E5: FY98 Class B Mishap Probability Table

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
Oct97	0.45	0.63	0.29	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nov97	0.45	0.64	0.29	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dec97	0.45	0.64	0.29	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jan98	0.45	0.64	0.29	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feb98	0.45	0.64	0.29	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mar98	0.44	0.64	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Apr98	0.44	0.64	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
May98	0.44	0.64	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jun98	0.44	0.65	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jul98	0.44	0.65	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aug98	0.43	0.65	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sep98	0.43	0.65	0.28	0.06	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table E6: FY98 Class C Mishap Probability Table

	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10
Oct97	1.80	0.17	0.30	0.27	0.16	0.07	0.03	0.01	0.00	0.00	0.00	0.00
Nov97	1.77	0.17	0.30	0.27	0.16	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Dec97	1.75	0.17	0.30	0.27	0.16	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Jan98	1.73	0.18	0.31	0.27	0.15	0.07	0.02	0.01	0.00	0.00	0.00	0.00
Feb98	1.70	0.18	0.31	0.26	0.15	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Mar98	1.68	0.19	0.31	0.26	0.15	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Apr98	1.66	0.19	0.32	0.26	0.14	0.06	0.02	0.01	0.00	0.00	0.00	0.00
May98	1.63	0.20	0.32	0.26	0.14	0.06	0.02	0.01	0.00	0.00	0.00	0.00
Jun98	1.61	0.20	0.32	0.26	0.14	0.06	0.02	0.00	0.00	0.00	0.00	0.00
Jul98	1.59	0.20	0.32	0.26	0.14	0.05	0.02	0.00	0.00	0.00	0.00	0.00
Aug98	1.57	0.21	0.33	0.26	0.13	0.05	0.02	0.00	0.00	0.00	0.00	0.00
Sep98	1.54	0.21	0.33	0.25	0.13	0.05	0.02	0.00	0.00	0.00	0.00	0.00

APPENDIX F: PREDICTED COSTS OF MAINTENACE-RELATED MISHAPS

Table F1: Predicted Maintenance-Related Flight Mishap Costs for FY98-FY02

FM	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Oct97	1.01	-	1,897,059	1,914,416	965,966	324,935	81,977	16,545	2,783	401	51	6	5,204,139
Nov97	1.00	-	1,897,137	1,898,383	949,815	316,813	79,255	15,861	2,645	378	47	5	5,160,341
Dec97	0.99	-	1,897,080	1,882,350	933,867	308,872	76,618	15,205	2,514	356	44	5	5,116,912
Jan98	0.98	-	1,896,889	1,866,320	918,121	301,109	74,064	14,574	2,390	336	41	5	5,073,848
Feb98	0.98	-	1,896,564	1,850,296	902,578	293,520	71,590	13,969	2,271	317	39	4	5,031,147
Mar98	0.97	-	1,896,107	1,834,282	887,236	286,102	69,193	13,387	2,158	298	36	4	4,988,805
Apr98	0.96	-	1,895,519	1,818,281	872,095	278,853	66,873	12,830	2,051	281	34	4	4,946,819
May98	0.95	-	1,894,802	1,802,296	857,153	271,769	64,625	12,294	1,949	265	31	3	4,905,187
Jun98	0.94	-	1,893,956	1,786,330	842,410	264,846	62,449	11,780	1,852	250	29	3	4,863,905
Jul98	0.94	-	1,892,983	1,770,386	827,865	258,083	60,342	11,287	1,759	235	27	3	4,822,970
Aug98	0.93	-	1,891,884	1,754,468	813,516	251,475	58,302	10,814	1,671	221	26	3	4,782,380
Sep98	0.92	-	1,890,661	1,738,577	799,363	245,021	56,328	10,359	1,588	209	24	2	4,742,132
Oct98	0.92	-	1,889,314	1,722,717	785,405	238,716	54,417	9,924	1,508	196	22	2	4,702,222
Nov98	0.90	-	1,887,845	1,706,891	771,641	232,559	52,567	9,506	1,432	185	21	2	4,662,649
Dec98	0.90	-	1,886,256	1,691,101	758,068	226,546	50,777	9,105	1,360	174	20	2	4,623,408
Jan99	0.89	-	1,884,547	1,675,349	744,687	220,674	49,044	8,720	1,292	164	18	2	4,584,497
Feb99	0.88	-	1,882,720	1,659,639	731,495	214,941	47,368	8,351	1,227	155	17	2	4,545,914
Mar99	0.87	-	1,880,777	1,643,973	718,492	209,343	45,746	7,997	1,165	145	16	2	4,507,656
Apr99	0.87	-	1,878,718	1,628,353	705,676	203,878	44,177	7,658	1,106	137	15	1	4,469,720
May99	0.86	-	1,876,545	1,612,781	693,046	198,544	42,659	7,333	1,050	129	14	1	4,432,103
Jun99	0.85	-	1,874,260	1,597,261	680,600	193,338	41,191	7,021	997	121	13	1	4,394,802
Jul99	0.85	-	1,871,863	1,581,793	668,337	188,256	39,771	6,722	947	114	12	1	4,357,816
Aug99	0.84	-	1,869,357	1,566,381	656,255	183,297	38,397	6,435	899	108	11	1	4,321,140
Sep99	0.83	-	1,866,743	1,551,026	644,353	178,458	37,069	6,160	853	101	11	1	4,284,774
Oct99	0.82	-	1,864,021	1,535,730	632,629	173,737	35,785	5,896	810	95	10	1	4,248,713
Nov99	0.82	-	1,861,194	1,520,496	621,082	169,130	34,543	5,644	768	90	9	1	4,212,956
Dec99	0.81	-	1,858,263	1,505,325	609,710	164,636	33,342	5,402	729	84	9	1	4,177,500
Jan00	0.80	-	1,855,229	1,490,219	598,512	160,252	32,181	5,170	692	79	8	1	4,142,342
Feb00	0.80	-	1,852,093	1,475,180	587,486	155,976	31,058	4,948	657	75	7	1	4,107,481
Mar00	0.79	-	1,848,858	1,460,210	576,630	151,805	29,974	4,735	623	70	7	1	4,072,912
Apr00	0.78	-	1,845,524	1,445,310	565,942	147,738	28,925	4,530	591	66	6	1	4,038,635
May00	0.78	-	1,842,094	1,430,482	555,422	143,771	27,912	4,335	561	62	6	1	4,004,646
Jun00	0.77	-	1,838,567	1,415,728	545,067	139,904	26,932	4,148	532	59	6	0	3,970,943

FM	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Jul00	0.76	-	1,834,947	1,401,049	534,876	136,132	25,986	3,968	505	55	5	0	3,937,523
Aug00	0.76	-	1,831,233	1,386,446	524,847	132,456	25,071	3,796	479	52	5	0	3,904,385
Sep00	0.75	-	1,827,429	1,371,922	514,977	128,871	24,187	3,632	454	49	5	0	3,871,526
Oct00	0.74	-	1,823,534	1,357,476	505,267	125,377	23,333	3,474	431	46	4	0	3,838,943
Nov00	0.74	-	1,819,551	1,343,112	495,713	121,971	22,508	3,323	409	43	4	0	3,806,635
Dec00	0.73	-	1,815,482	1,328,829	486,314	118,651	21,712	3,178	388	41	4	0	3,774,598
Jan01	0.73	-	1,811,326	1,314,630	477,068	115,416	20,942	3,040	368	38	3	0	3,742,831
Feb01	0.72	-	1,807,086	1,300,515	467,974	112,263	20,198	2,907	349	36	3	0	3,711,332
Mar01	0.71	-	1,802,764	1,286,485	459,030	109,191	19,480	2,780	331	34	3	0	3,680,097
Apr01	0.71	-	1,798,360	1,272,542	450,233	106,197	18,787	2,659	314	32	3	0	3,649,126
May01	0.70	-	1,793,876	1,258,686	441,583	103,280	18,117	2,542	297	30	3	0	3,618,415
Jun01	0.70	-	1,789,314	1,244,919	433,078	100,438	17,470	2,431	282	28	2	0	3,587,962
Jul01	0.69	-	1,784,675	1,231,241	424,715	97,670	16,846	2,324	267	26	2	0	3,557,766
Aug01	0.68	-	1,779,960	1,217,654	416,493	94,973	16,243	2,222	253	25	2	0	3,527,824
Sep01	0.68	-	1,775,170	1,204,157	408,410	92,346	15,660	2,125	240	23	2	0	3,498,134
Oct01	0.67	-	1,770,308	1,190,753	400,465	89,787	15,098	2,031	228	22	2	0	3,468,694
Nov01	0.67	-	1,765,375	1,177,441	392,655	87,296	14,556	1,942	216	21	2	0	3,439,501
Dec01	0.66	-	1,760,371	1,164,222	384,979	84,869	14,032	1,856	205	19	2	0	3,410,555
Jan02	0.66	-	1,755,298	1,151,097	377,436	82,506	13,526	1,774	194	18	1	0	3,381,851
Feb02	0.65	-	1,750,158	1,138,068	370,023	80,204	13,039	1,696	184	17	1	0	3,353,390
Mar02	0.64	-	1,744,952	1,125,133	362,739	77,964	12,568	1,621	174	16	1	0	3,325,168
Apr02	0.64	-	1,739,682	1,112,294	355,582	75,782	12,113	1,549	165	15	1	0	3,297,183
May02	0.64	-	1,734,348	1,099,551	348,550	73,658	11,675	1,480	156	14	1	0	3,269,434
Jun02	0.63	-	1,728,952	1,086,905	341,641	71,591	11,251	1,415	148	13	1	0	3,241,919
Jul02	0.62	-	1,723,496	1,074,357	334,855	69,578	10,843	1,352	140	13	1	0	3,214,635
Aug02	0.62	-	1,717,980	1,061,906	328,189	67,619	10,449	1,292	133	12	1	0	3,187,581
Sep02	0.61	-	1,712,406	1,049,553	321,641	65,712	10,069	1,234	126	11	1	0	3,160,754

245,959,174

Table F2: Predicted Maintenance-Related Flight-Related Mishap Costs for FY98-FY02

FRM	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Oct97	0.16	-	15,658	2,573	211	12	0	0	0	0	0	0	18,455
Nov97	0.16	-	15,473	2,506	203	11	0	0	0	0	0	0	18,193
Dec97	0.16	-	15,289	2,441	195	10	0	0	0	0	0	0	17,936
Jan98	0.16	-	15,107	2,378	187	10	0	0	0	0	0	0	17,682
Feb98	0.16	-	14,926	2,317	180	9	0	0	0	0	0	0	17,432
Mar98	0.15	-	14,747	2,256	173	9	0	0	0	0	0	0	17,185
Apr98	0.15	-	14,570	2,198	166	8	0	0	0	0	0	0	16,942
May98	0.15	-	14,395	2,141	159	8	0	0	0	0	0	0	16,702
Jun98	0.15	-	14,221	2,085	153	7	0	0	0	0	0	0	16,466
Jul98	0.14	-	14,049	2,030	147	7	0	0	0	0	0	0	16,233
Aug98	0.14	-	13,878	1,977	141	7	0	0	0	0	0	0	16,003
Sep98	0.14	-	13,709	1,926	135	6	0	0	0	0	0	0	15,777
Oct98	0.14	-	13,542	1,875	130	6	0	0	0	0	0	0	15,554
Nov98	0.14	-	13,377	1,826	125	6	0	0	0	0	0	0	15,333
Dec98	0.13	-	13,213	1,778	120	5	0	0	0	0	0	0	15,116
Jan99	0.13	-	13,051	1,732	115	5	0	0	0	0	0	0	14,903
Feb99	0.13	-	12,890	1,686	110	5	0	0	0	0	0	0	14,692
Mar99	0.13	-	12,731	1,642	106	5	0	0	0	0	0	0	14,484
Apr99	0.13	-	12,574	1,599	102	4	0	0	0	0	0	0	14,279
May99	0.13	-	12,419	1,556	98	4	0	0	0	0	0	0	14,077
Jun99	0.12	-	12,265	1,515	94	4	0	0	0	0	0	0	13,878
Jul99	0.12	-	12,112	1,475	90	4	0	0	0	0	0	0	13,681
Aug99	0.12	-	11,961	1,436	86	3	0	0	0	0	0	0	13,488
Sep99	0.12	-	11,812	1,398	83	3	0	0	0	0	0	0	13,297
Oct99	0.12	-	11,665	1,361	79	3	0	0	0	0	0	0	13,108
Nov99	0.12	-	11,518	1,325	76	3	0	0	0	0	0	0	12,923
Dec99	0.11	-	11,374	1,290	73	3	0	0	0	0	0	0	12,740
Jan00	0.11	-	11,231	1,256	70	3	0	0	0	0	0	0	12,560
Feb00	0.11	-	11,090	1,223	67	2	0	0	0	0	0	0	12,382
Mar00	0.11	-	10,950	1,190	65	2	0	0	0	0	0	0	12,207
Apr00	0.11	-	10,811	1,158	62	2	0	0	0	0	0	0	12,034
May00	0.11	-	10,675	1,128	60	2	0	0	0	0	0	0	11,864
Jun00	0.10	-	10,539	1,097	57	2	0	0	0	0	0	0	11,696

FRM	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Jul00	0.10	–	10,405	1,068	55	2	0	0	0	0	0	0	11,530
Aug00	0.10	–	10,273	1,040	53	2	0	0	0	0	0	0	11,367
Sep00	0.10	–	10,142	1,012	50	2	0	0	0	0	0	0	11,206
Oct00	0.10	–	10,013	985	48	2	0	0	0	0	0	0	11,048
Nov00	0.10	–	9,885	959	46	2	0	0	0	0	0	0	10,891
Dec00	0.10	–	9,758	933	45	1	0	0	0	0	0	0	10,737
Jan01	0.09	–	9,633	908	43	1	0	0	0	0	0	0	10,585
Feb01	0.09	–	9,510	884	41	1	0	0	0	0	0	0	10,436
Mar01	0.09	–	9,387	860	39	1	0	0	0	0	0	0	10,288
Apr01	0.09	–	9,267	837	38	1	0	0	0	0	0	0	10,142
May01	0.09	–	9,147	814	36	1	0	0	0	0	0	0	9,999
Jun01	0.09	–	9,029	792	35	1	0	0	0	0	0	0	9,857
Jul01	0.09	–	8,912	771	33	1	0	0	0	0	0	0	9,718
Aug01	0.09	–	8,797	750	32	1	0	0	0	0	0	0	9,580
Sep01	0.08	–	8,683	730	31	1	0	0	0	0	0	0	9,445
Oct01	0.08	–	8,570	710	29	1	0	0	0	0	0	0	9,311
Nov01	0.08	–	8,459	691	28	1	0	0	0	0	0	0	9,179
Dec01	0.08	–	8,349	673	27	1	0	0	0	0	0	0	9,049
Jan02	0.08	–	8,240	654	26	1	0	0	0	0	0	0	8,921
Feb02	0.08	–	8,133	637	25	1	0	0	0	0	0	0	8,795
Mar02	0.08	–	8,026	620	24	1	0	0	0	0	0	0	8,671
Apr02	0.08	–	7,922	603	23	1	0	0	0	0	0	0	8,548
May02	0.08	–	7,818	587	22	1	0	0	0	0	0	0	8,427
Jun02	0.07	–	7,715	571	21	1	0	0	0	0	0	0	8,308
Jul02	0.07	–	7,614	555	20	0	0	0	0	0	0	0	8,190
Aug02	0.07	–	7,514	540	19	0	0	0	0	0	0	0	8,074
Sep02	0.07	–	7,415	526	19	0	0	0	0	0	0	0	7,960

749,565

Table F3: Predicted Maintenance-Related Aircraft-Ground Mishap Costs for FY98-FY02

AGM	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Oct97	1.77	-	25,092	44,422	39,322	23,205	10,270	3,636	1,073	271	60	12	147,365
Nov97	1.75	-	25,267	44,326	38,881	22,736	9,972	3,499	1,023	256	56	11	146,027
Dec97	1.74	-	25,440	44,224	38,439	22,274	9,680	3,366	975	242	53	10	144,702
Jan98	1.72	-	25,610	44,115	37,997	21,818	9,396	3,237	929	229	49	9	143,389
Feb98	1.71	-	25,777	44,001	37,554	21,368	9,119	3,113	886	216	46	9	142,088
Mar98	1.69	-	25,942	43,880	37,111	20,924	8,848	2,993	844	204	43	8	140,798
Apr98	1.68	-	26,104	43,754	36,668	20,487	8,585	2,878	804	192	40	8	139,520
May98	1.66	-	26,264	43,622	36,226	20,056	8,328	2,766	766	182	38	7	138,254
Jun98	1.65	-	26,421	43,484	35,784	19,631	8,078	2,659	729	171	35	6	136,999
Jul98	1.63	-	26,575	43,341	35,342	19,213	7,834	2,555	695	162	33	6	135,756
Aug98	1.62	-	26,727	43,193	34,902	18,801	7,596	2,455	661	153	31	6	134,524
Sep98	1.60	-	26,875	43,039	34,462	18,396	7,365	2,359	630	144	29	5	133,303
Oct98	1.59	-	27,021	42,880	34,023	17,997	7,140	2,266	599	136	27	5	132,093
Nov98	1.57	-	27,164	42,716	33,585	17,604	6,920	2,176	570	128	25	4	130,894
Dec98	1.56	-	27,305	42,547	33,148	17,217	6,707	2,090	543	121	24	4	129,706
Jan99	1.54	-	27,442	42,373	32,713	16,837	6,499	2,007	517	114	22	4	128,529
Feb99	1.53	-	27,577	42,195	32,280	16,463	6,297	1,927	491	107	21	3	127,363
Mar99	1.52	-	27,709	42,011	31,848	16,096	6,101	1,850	467	101	19	3	126,207
Apr99	1.50	-	27,838	41,824	31,418	15,734	5,910	1,776	445	95	18	3	125,061
May99	1.49	-	27,964	41,632	30,990	15,379	5,724	1,704	423	90	17	3	123,926
Jun99	1.48	-	28,087	41,436	30,564	15,030	5,543	1,636	402	85	16	3	122,801
Jul99	1.46	-	28,207	41,236	30,140	14,687	5,368	1,569	382	80	15	2	121,687
Aug99	1.45	-	28,325	41,031	29,719	14,350	5,197	1,506	364	75	14	2	120,582
Sep99	1.44	-	28,439	40,823	29,300	14,019	5,031	1,444	346	71	13	2	119,488
Oct99	1.42	-	28,551	40,611	28,883	13,695	4,870	1,385	328	67	12	2	118,403
Nov99	1.41	-	28,659	40,395	28,469	13,376	4,713	1,329	312	63	11	2	117,329
Dec99	1.40	-	28,765	40,176	28,057	13,063	4,561	1,274	297	59	10	2	116,264
Jan00	1.38	-	28,867	39,953	27,649	12,756	4,414	1,222	282	56	10	1	115,209
Feb00	1.37	-	28,967	39,727	27,243	12,454	4,270	1,171	268	52	9	1	114,163
Mar00	1.36	-	29,063	39,498	26,840	12,159	4,131	1,123	254	49	8	1	113,127
Apr00	1.35	-	29,157	39,266	26,439	11,869	3,996	1,076	242	46	8	1	112,100
May00	1.33	-	29,248	39,030	26,042	11,584	3,865	1,031	229	44	7	1	111,083
Jun00	1.32	-	29,335	38,792	25,649	11,306	3,738	988	218	41	7	1	110,074

AGM	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Jul00	1.31	-	29,420	38,551	25,258	11,032	3,614	947	207	39	6	1	109,075
Aug00	1.30	-	29,502	38,307	24,870	10,764	3,494	907	196	36	6	1	108,085
Sep00	1.29	-	29,581	38,061	24,486	10,502	3,378	869	186	34	6	1	107,104
Oct00	1.28	-	29,657	37,812	24,105	10,245	3,266	833	177	32	5	1	106,132
Nov00	1.26	-	29,729	37,561	23,728	9,993	3,156	798	168	30	5	1	105,169
Dec00	1.25	-	29,799	37,308	23,354	9,746	3,050	764	159	29	4	1	104,214
Jan01	1.24	-	29,866	37,052	22,983	9,504	2,948	731	151	27	4	1	103,268
Feb01	1.23	-	29,930	36,795	22,617	9,268	2,848	700	143	25	4	1	102,331
Mar01	1.22	-	29,992	36,535	22,253	9,036	2,752	670	136	24	4	0	101,402
Apr01	1.21	-	30,050	36,274	21,893	8,809	2,659	642	129	22	3	0	100,482
May01	1.20	-	30,105	36,011	21,537	8,587	2,568	614	122	21	3	0	99,570
Jun01	1.19	-	30,157	35,746	21,185	8,370	2,480	588	116	20	3	0	98,666
Jul01	1.17	-	30,207	35,480	20,836	8,158	2,395	563	110	18	3	0	97,771
Aug01	1.16	-	30,254	35,212	20,491	7,950	2,313	538	104	17	3	0	96,883
Sep01	1.15	-	30,297	34,943	20,150	7,747	2,234	515	99	16	2	0	96,004
Oct01	1.14	-	30,338	34,672	19,813	7,548	2,157	493	94	15	2	0	95,133
Nov01	1.13	-	30,376	34,401	19,479	7,353	2,082	472	89	14	2	0	94,269
Dec01	1.12	-	30,412	34,128	19,150	7,163	2,010	451	84	14	2	0	93,413
Jan02	1.11	-	30,444	33,855	18,824	6,977	1,940	431	80	13	2	0	92,566
Feb02	1.10	-	30,474	33,580	18,501	6,796	1,872	413	76	12	2	0	91,725
Mar02	1.09	-	30,501	33,305	18,183	6,618	1,807	395	72	11	2	0	90,893
Apr02	1.08	-	30,525	33,029	17,869	6,445	1,743	377	68	11	1	0	90,068
May02	1.07	-	30,547	32,752	17,558	6,275	1,682	361	64	10	1	0	89,250
Jun02	1.06	-	30,565	32,475	17,252	6,110	1,623	345	61	9	1	0	88,440
Jul02	1.05	-	30,581	32,197	16,949	5,948	1,566	330	58	9	1	0	87,638
Aug02	1.04	-	30,595	31,918	16,650	5,790	1,510	315	55	8	1	0	86,842
Sep02	1.03	-	30,605	31,640	16,355	5,636	1,457	301	52	8	1	0	86,054
													6,841,264

Table F4: Predicted Maintenance-Related Class A Mishap Costs for FY98-FY02

Class A	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Oct97	0.36	-	3,188,126	1,150,001	207,411	24,939	2,249	162	10	1	0	0	4,572,898
Nov97	0.36	-	3,166,195	1,129,862	201,596	23,980	2,139	153	9	0	0	0	4,523,935
Dec97	0.35	-	3,144,286	1,110,030	195,937	23,057	2,035	144	8	0	0	0	4,475,497
Jan98	0.35	-	3,122,400	1,090,501	190,429	22,169	1,936	135	8	0	0	0	4,427,578
Feb98	0.35	-	3,100,541	1,071,272	185,068	21,314	1,841	127	7	0	0	0	4,380,172
Mar98	0.34	-	3,078,711	1,052,340	179,851	20,492	1,751	120	7	0	0	0	4,333,273
Apr98	0.34	-	3,056,915	1,033,702	174,774	19,700	1,665	113	6	0	0	0	4,286,876
May98	0.33	-	3,035,153	1,015,355	169,834	18,938	1,584	106	6	0	0	0	4,240,976
Jun98	0.33	-	3,013,430	997,294	165,027	18,205	1,506	100	5	0	0	0	4,195,568
Jul98	0.33	-	2,991,748	979,517	160,350	17,500	1,432	94	5	0	0	0	4,150,646
Aug98	0.32	-	2,970,109	962,020	155,799	16,821	1,362	88	5	0	0	0	4,106,205
Sep98	0.32	-	2,948,515	944,800	151,372	16,168	1,295	83	4	0	0	0	4,062,239
Oct98	0.32	-	2,926,970	927,855	147,066	15,540	1,232	78	4	0	0	0	4,018,745
Nov98	0.31	-	2,905,476	911,179	142,876	14,936	1,171	73	4	0	0	0	3,975,716
Dec98	0.31	-	2,884,035	894,771	138,801	14,354	1,113	69	4	0	0	0	3,933,148
Jan99	0.31	-	2,862,649	878,627	134,838	13,795	1,059	65	3	0	0	0	3,891,035
Feb99	0.30	-	2,841,320	862,743	130,982	13,257	1,006	61	3	0	0	0	3,849,374
Mar99	0.30	-	2,820,051	847,117	127,233	12,740	957	57	3	0	0	0	3,808,158
Apr99	0.30	-	2,798,844	831,744	123,586	12,242	910	54	3	0	0	0	3,767,384
May99	0.29	-	2,777,701	816,623	120,040	11,764	865	51	2	0	0	0	3,727,046
Jun99	0.29	-	2,756,624	801,749	116,592	11,303	822	48	2	0	0	0	3,687,141
Jul99	0.29	-	2,735,614	787,120	113,239	10,861	781	45	2	0	0	0	3,647,662
Aug99	0.28	-	2,714,674	772,731	109,979	10,435	743	42	2	0	0	0	3,608,606
Sep99	0.28	-	2,693,806	758,581	106,809	10,026	706	40	2	0	0	0	3,569,969
Oct99	0.28	-	2,673,010	744,665	103,727	9,632	671	37	2	0	0	0	3,531,745
Nov99	0.28	-	2,652,290	730,982	100,731	9,254	638	35	2	0	0	0	3,493,930
Dec99	0.27	-	2,631,646	717,526	97,818	8,890	606	33	2	0	0	0	3,456,521
Jan00	0.27	-	2,611,080	704,296	94,986	8,540	576	31	1	0	0	0	3,419,512
Feb00	0.27	-	2,590,594	691,289	92,234	8,204	547	29	1	0	0	0	3,382,899
Mar00	0.26	-	2,570,189	678,501	89,558	7,881	520	27	1	0	0	0	3,346,678
Apr00	0.26	-	2,549,867	665,929	86,958	7,570	494	26	1	0	0	0	3,310,845
May00	0.26	-	2,529,629	653,570	84,430	7,271	470	24	1	0	0	0	3,275,395
Jun00	0.26	-	2,509,477	641,421	81,973	6,984	446	23	1	0	0	0	3,240,325

Class A	$\hat{\lambda_t}$	0	1	2	3	4	5	6	7	8	9	10	Total
Jul00	0.25	-	2,489,411	629,479	79,586	6,708	424	21	1	0	0	0	3,205,631
Aug00	0.25	-	2,469,434	617,742	77,266	6,443	403	20	1	0	0	0	3,171,308
Sep00	0.25	-	2,449,546	606,206	75,011	6,188	383	19	1	0	0	0	3,137,353
Oct00	0.24	-	2,429,748	594,868	72,820	5,943	364	18	1	0	0	0	3,103,761
Nov00	0.24	-	2,410,042	583,726	70,691	5,707	346	17	1	0	0	0	3,070,529
Dec00	0.24	-	2,390,428	572,776	68,622	5,481	328	16	1	0	0	0	3,037,653
Jan01	0.24	-	2,370,909	562,017	66,612	5,263	312	15	1	0	0	0	3,005,128
Feb01	0.23	-	2,351,484	551,444	64,659	5,054	296	14	1	0	0	0	2,972,952
Mar01	0.23	-	2,332,155	541,055	62,762	4,854	282	13	1	0	0	0	2,941,121
Apr01	0.23	-	2,312,923	530,848	60,918	4,661	267	12	0	0	0	0	2,909,630
May01	0.23	-	2,293,788	520,819	59,128	4,475	254	12	0	0	0	0	2,878,476
Jun01	0.22	-	2,274,752	510,967	57,388	4,297	241	11	0	0	0	0	2,847,656
Jul01	0.22	-	2,255,815	501,288	55,698	4,126	229	10	0	0	0	0	2,817,166
Aug01	0.22	-	2,236,978	491,779	54,057	3,961	218	10	0	0	0	0	2,787,003
Sep01	0.22	-	2,218,242	482,439	52,462	3,803	207	9	0	0	0	0	2,757,162
Oct01	0.22	-	2,199,607	473,264	50,913	3,651	196	8	0	0	0	0	2,727,641
Nov01	0.21	-	2,181,074	464,252	49,409	3,506	187	8	0	0	0	0	2,698,436
Dec01	0.21	-	2,162,645	455,400	47,948	3,366	177	7	0	0	0	0	2,669,544
Jan02	0.21	-	2,144,318	446,707	46,529	3,231	168	7	0	0	0	0	2,640,961
Feb02	0.21	-	2,126,096	438,168	45,151	3,102	160	7	0	0	0	0	2,612,684
Mar02	0.20	-	2,107,978	429,783	43,813	2,978	152	6	0	0	0	0	2,584,710
Apr02	0.20	-	2,089,965	421,548	42,513	2,858	144	6	0	0	0	0	2,557,035
May02	0.20	-	2,072,058	413,461	41,251	2,744	137	5	0	0	0	0	2,529,657
Jun02	0.20	-	2,054,257	405,520	40,026	2,634	130	5	0	0	0	0	2,502,572
Jul02	0.20	-	2,036,562	397,723	38,836	2,528	123	5	0	0	0	0	2,475,776
Aug02	0.19	-	2,018,973	390,066	37,680	2,427	117	5	0	0	0	0	2,449,268
Sep02	0.19	-	2,001,492	382,548	36,559	2,329	111	4	0	0	0	0	2,423,044
														203,211,552

Table F5: Predicted Maintenance-Related Class B Mishap Costs for FY98-FY02

Class B	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Oct97	0.45	-	110,439	50,221	11,419	1,731	197	18	1	0	0	0	174,026
Nov97	0.45	-	110,162	49,865	11,286	1,703	193	17	1	0	0	0	173,228
Dec97	0.45	-	109,885	49,512	11,154	1,675	189	17	1	0	0	0	172,434
Jan98	0.45	-	109,607	49,160	11,024	1,648	185	17	1	0	0	0	171,643
Feb98	0.45	-	109,329	48,811	10,896	1,621	181	16	1	0	0	0	170,856
Mar98	0.44	-	109,051	48,463	10,769	1,595	177	16	1	0	0	0	170,072
Apr98	0.44	-	108,772	48,118	10,643	1,569	174	15	1	0	0	0	169,292
May98	0.44	-	108,494	47,774	10,518	1,544	170	15	1	0	0	0	168,516
Jun98	0.44	-	108,214	47,433	10,395	1,519	166	15	1	0	0	0	167,743
Jul98	0.44	-	107,935	47,093	10,274	1,494	163	14	1	0	0	0	166,974
Aug98	0.43	-	107,655	46,756	10,153	1,470	160	14	1	0	0	0	166,208
Sep98	0.43	-	107,375	46,420	10,034	1,446	156	14	1	0	0	0	165,446
Oct98	0.43	-	107,095	46,087	9,916	1,422	153	13	1	0	0	0	164,687
Nov98	0.43	-	106,814	45,755	9,800	1,399	150	13	1	0	0	0	163,932
Dec98	0.43	-	106,533	45,426	9,685	1,377	147	13	1	0	0	0	163,180
Jan99	0.42	-	106,252	45,098	9,571	1,354	144	12	1	0	0	0	162,432
Feb99	0.42	-	105,971	44,772	9,458	1,332	141	12	1	0	0	0	161,687
Mar99	0.42	-	105,690	44,449	9,347	1,310	138	12	1	0	0	0	160,946
Apr99	0.42	-	105,408	44,127	9,236	1,289	135	11	1	0	0	0	160,208
May99	0.42	-	105,127	43,807	9,127	1,268	132	11	1	0	0	0	159,473
Jun99	0.41	-	104,845	43,489	9,020	1,247	129	11	1	0	0	0	158,742
Jul99	0.41	-	104,563	43,174	8,913	1,227	127	10	1	0	0	0	158,014
Aug99	0.41	-	104,280	42,860	8,808	1,207	124	10	1	0	0	0	157,289
Sep99	0.41	-	103,998	42,547	8,703	1,187	121	10	1	0	0	0	156,568
Oct99	0.41	-	103,715	42,237	8,600	1,167	119	10	1	0	0	0	155,850
Nov99	0.41	-	103,433	41,929	8,499	1,148	116	9	1	0	0	0	155,135
Dec99	0.40	-	103,150	41,623	8,398	1,130	114	9	1	0	0	0	154,424
Jan00	0.40	-	102,867	41,318	8,298	1,111	112	9	1	0	0	0	153,716
Feb00	0.40	-	102,584	41,016	8,200	1,093	109	9	1	0	0	0	153,011
Mar00	0.40	-	102,301	40,715	8,102	1,075	107	9	1	0	0	0	152,309
Apr00	0.40	-	102,018	40,416	8,006	1,057	105	8	1	0	0	0	151,611
May00	0.39	-	101,735	40,119	7,910	1,040	103	8	1	0	0	0	150,915
Jun00	0.39	-	101,452	39,824	7,816	1,023	100	8	1	0	0	0	150,223

Class B	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Jul00	0.39	-	101,168	39,531	7,723	1,006	98	8	1	0	0	0	149,534
Aug00	0.39	-	100,885	39,239	7,631	989	96	7	0	0	0	0	148,849
Sep00	0.39	-	100,602	38,949	7,540	973	94	7	0	0	0	0	148,166
Oct00	0.39	-	100,318	38,662	7,450	957	92	7	0	0	0	0	147,487
Nov00	0.38	-	100,035	38,376	7,361	941	90	7	0	0	0	0	146,810
Dec00	0.38	-	99,752	38,091	7,273	926	88	7	0	0	0	0	146,137
Jan01	0.38	-	99,468	37,809	7,186	910	87	7	0	0	0	0	145,467
Feb01	0.38	-	99,185	37,528	7,100	895	85	6	0	0	0	0	144,800
Mar01	0.38	-	98,901	37,250	7,015	881	83	6	0	0	0	0	144,136
Apr01	0.37	-	98,618	36,972	6,931	866	81	6	0	0	0	0	143,475
May01	0.37	-	98,335	36,697	6,847	852	79	6	0	0	0	0	142,817
Jun01	0.37	-	98,051	36,424	6,765	838	78	6	0	0	0	0	142,162
Jul01	0.37	-	97,768	36,152	6,684	824	76	6	0	0	0	0	141,510
Aug01	0.37	-	97,485	35,882	6,604	810	75	5	0	0	0	0	140,861
Sep01	0.37	-	97,202	35,614	6,524	797	73	5	0	0	0	0	140,215
Oct01	0.36	-	96,919	35,347	6,446	784	71	5	0	0	0	0	139,572
Nov01	0.36	-	96,636	35,082	6,368	771	70	5	0	0	0	0	138,932
Dec01	0.36	-	96,353	34,819	6,291	758	68	5	0	0	0	0	138,295
Jan02	0.36	-	96,070	34,558	6,215	745	67	5	0	0	0	0	137,661
Feb02	0.36	-	95,787	34,298	6,140	733	66	5	0	0	0	0	137,030
Mar02	0.36	-	95,505	34,040	6,066	721	64	5	0	0	0	0	136,401
Apr02	0.35	-	95,222	33,784	5,993	709	63	4	0	0	0	0	135,776
May02	0.35	-	94,940	33,529	5,921	697	62	4	0	0	0	0	135,153
Jun02	0.35	-	94,658	33,276	5,849	685	60	4	0	0	0	0	134,533
Jul02	0.35	-	94,376	33,025	5,778	674	59	4	0	0	0	0	133,916
Aug02	0.35	-	94,094	32,775	5,708	663	58	4	0	0	0	0	133,302
Sep02	0.35	-	93,812	32,527	5,639	652	56	4	0	0	0	0	132,691

9,146,477

Table F6: Predicted Maintenance-Related Class C Mishap Costs for FY98-FY02

Class C	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Oct97	1.80	–	13,805	24,825	22,321	13,380	6,015	2,163	648	167	37	7	83,370
Nov97	1.77	–	13,956	24,752	21,950	12,977	5,754	2,041	603	153	34	7	82,227
Dec97	1.75	–	14,104	24,671	21,578	12,582	5,502	1,925	561	140	31	6	81,099
Jan98	1.73	–	14,248	24,581	21,205	12,195	5,260	1,815	522	129	28	5	79,986
Feb98	1.70	–	14,389	24,484	20,831	11,815	5,026	1,711	485	118	25	5	78,889
Mar98	1.68	–	14,527	24,380	20,458	11,444	4,802	1,612	451	108	23	4	77,807
Apr98	1.66	–	14,661	24,268	20,084	11,081	4,586	1,518	419	99	20	4	76,740
May98	1.63	–	14,792	24,148	19,711	10,726	4,378	1,429	389	91	19	3	75,687
Jun98	1.61	–	14,920	24,022	19,340	10,380	4,178	1,345	361	83	17	3	74,649
Jul98	1.59	–	15,044	23,890	18,969	10,041	3,986	1,266	335	76	15	3	73,625
Aug98	1.57	–	15,164	23,751	18,600	9,711	3,802	1,191	311	70	14	2	72,615
Sep98	1.54	–	15,281	23,605	18,232	9,388	3,626	1,120	288	64	12	2	71,619
Oct98	1.52	–	15,394	23,454	17,867	9,074	3,456	1,053	267	58	11	2	70,636
Nov98	1.50	–	15,503	23,297	17,504	8,767	3,294	990	248	53	10	2	69,667
Dec98	1.48	–	15,609	23,134	17,143	8,469	3,138	930	230	49	9	1	68,712
Jan99	1.46	–	15,711	22,966	16,785	8,178	2,989	874	213	44	8	1	67,769
Feb99	1.44	–	15,810	22,792	16,430	7,895	2,846	821	197	41	7	1	66,840
Mar99	1.42	–	15,904	22,614	16,078	7,620	2,709	770	183	37	7	1	65,923
Apr99	1.40	–	15,995	22,431	15,729	7,353	2,578	723	169	34	6	1	65,018
May99	1.38	–	16,082	22,244	15,383	7,093	2,453	678	156	31	5	1	64,126
Jun99	1.36	–	16,165	22,052	15,042	6,840	2,333	636	145	28	5	1	63,247
Jul99	1.35	–	16,245	21,857	14,704	6,594	2,218	597	134	26	4	1	62,379
Aug99	1.33	–	16,320	21,657	14,370	6,356	2,109	560	124	23	4	1	61,523
Sep99	1.31	–	16,392	21,454	14,040	6,125	2,004	525	114	21	4	1	60,679
Oct99	1.29	–	16,460	21,248	13,714	5,901	1,904	492	106	20	3	0	59,847
Nov99	1.27	–	16,524	21,038	13,392	5,683	1,809	461	98	18	3	0	59,026
Dec99	1.26	–	16,585	20,825	13,075	5,473	1,718	431	90	16	3	0	58,216
Jan00	1.24	–	16,642	20,610	12,762	5,268	1,631	404	83	15	2	0	57,418
Feb00	1.22	–	16,694	20,392	12,454	5,071	1,548	378	77	13	2	0	56,630
Mar00	1.20	–	16,744	20,171	12,150	4,879	1,469	354	71	12	2	0	55,853
Apr00	1.19	–	16,789	19,949	11,851	4,694	1,394	331	66	11	2	0	55,087
May00	1.17	–	16,831	19,724	11,557	4,514	1,323	310	61	10	1	0	54,331
Jun00	1.16	–	16,869	19,497	11,268	4,341	1,254	290	56	9	1	0	53,586

Class C	$\hat{\lambda}_t$	0	1	2	3	4	5	6	7	8	9	10	Total
Jul00	1.14	–	16,904	19,269	10,983	4,173	1,189	271	52	8	1	0	52,851
Aug00	1.12	–	16,934	19,040	10,703	4,011	1,127	254	48	8	1	0	52,126
Sep00	1.11	–	16,962	18,809	10,428	3,855	1,069	237	44	7	1	0	51,411
Oct00	1.09	–	16,985	18,577	10,158	3,703	1,013	221	40	6	1	0	50,705
Nov00	1.08	–	17,006	18,344	9,893	3,557	959	207	37	6	1	0	50,010
Dec00	1.06	–	17,022	18,110	9,633	3,416	909	193	34	5	1	0	49,324
Jan01	1.05	–	17,036	17,875	9,378	3,280	860	181	32	5	1	0	48,647
Feb01	1.03	–	17,046	17,640	9,128	3,149	815	169	29	4	1	0	47,980
Mar01	1.02	–	17,052	17,405	8,883	3,022	771	157	27	4	0	0	47,322
Apr01	1.01	–	17,055	17,169	8,642	2,900	730	147	25	4	0	0	46,672
May01	0.99	–	17,055	16,934	8,407	2,782	691	137	23	3	0	0	46,032
Jun01	0.98	–	17,052	16,698	8,176	2,669	653	128	21	3	0	0	45,401
Jul01	0.97	–	17,046	16,463	7,950	2,559	618	119	19	3	0	0	44,778
Aug01	0.95	–	17,036	16,228	7,729	2,454	584	111	18	2	0	0	44,164
Sep01	0.94	–	17,023	15,993	7,513	2,353	553	104	16	2	0	0	43,558
Oct01	0.93	–	17,008	15,759	7,301	2,255	522	97	15	2	0	0	42,960
Nov01	0.91	–	16,989	15,526	7,095	2,161	494	90	14	2	0	0	42,371
Dec01	0.90	–	16,967	15,294	6,893	2,071	467	84	13	2	0	0	41,790
Jan02	0.89	–	16,943	15,062	6,695	1,984	441	78	12	1	0	0	41,216
Feb02	0.88	–	16,915	14,831	6,502	1,900	417	73	11	1	0	0	40,651
Mar02	0.86	–	16,885	14,602	6,314	1,820	393	68	10	1	0	0	40,093
Apr02	0.85	–	16,852	14,373	6,130	1,743	372	63	9	1	0	0	39,543
May02	0.84	–	16,817	14,146	5,950	1,668	351	59	8	1	0	0	39,001
Jun02	0.83	–	16,778	13,921	5,775	1,597	331	55	8	1	0	0	38,466
Jul02	0.82	–	16,738	13,696	5,604	1,529	313	51	7	1	0	0	37,938
Aug02	0.81	–	16,694	13,474	5,437	1,463	295	48	6	1	0	0	37,418
Sep02	0.80	–	16,649	13,252	5,274	1,399	278	44	6	1	0	0	36,904
													3,424,157

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